The
ENGINEERS' DIGEST
REVIEW OF WORLD ENGINEERING PROGRESS

VOL. XVIII No. 12 DECEMBER, 1957

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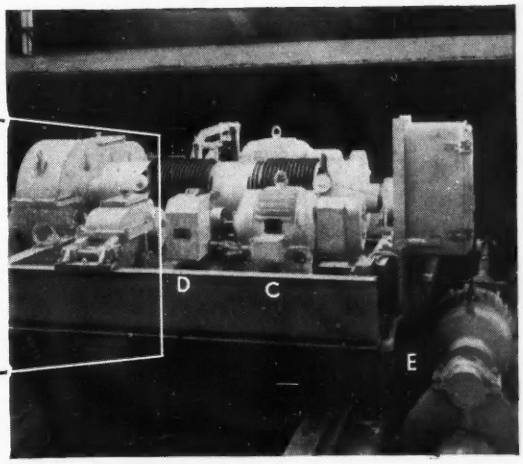
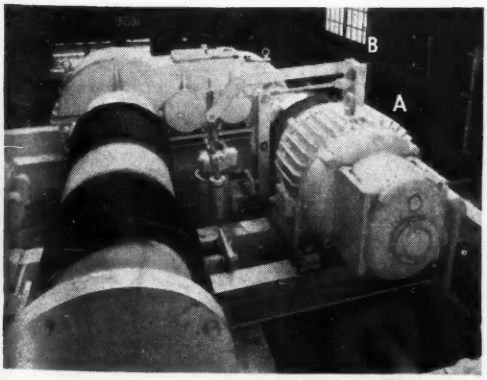
ON TOP OF THE JOB



Metrovick equipment is well on top in this 10-ton Wharton overhead shop crane. The hoist is an 18-h.p. 720 r.p.m. M-V motor fitted with a thrustor-operated brake giving precise control with stable creeping speed on load. The need for inching is thus eliminated. Drives for the long travel and cross-traverse are M-V 10-h.p. 715 r.p.m. and 3-h.p. 700 r.p.m. type MZ slipring motors respectively. A 6-inch Perigrip brake operates on the cross traverse. Write for details of the range of M-V a.c. and d.c. motors, control gear and Perigrip electromagnetic brakes for crane drives.



In the illustration (left) A is the 18-h.p. 720 r.p.m. hoist motor fitted with Stacreep thrustor control B. The long-travel drive, motor E, is shown at the top of page. The 3 h.p. cross traverse motor is seen at C and the 6-inch Perigrip brake at D.

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The ENGINEERS' DIGEST

REVIEW OF WORLD ENGINEERING PROGRESS

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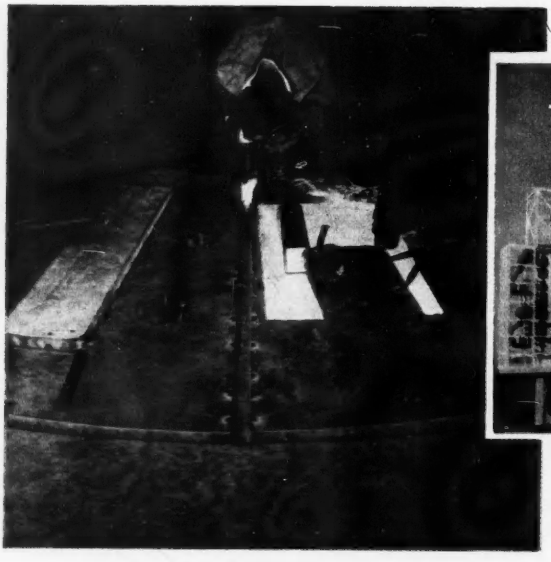
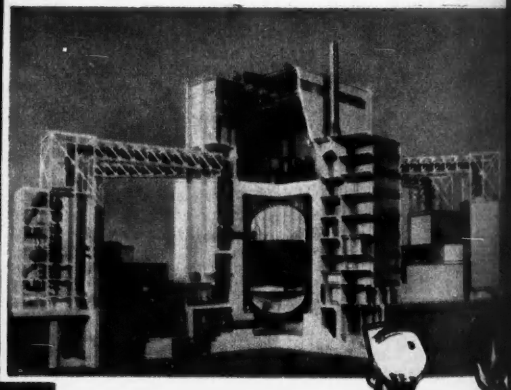
Welding begins inside the bowl of the reactor vessel. Six teams of John Thompson welders work outwards from the centre, welding the 3in. thick steel plates which have been assembled and are temporarily held in position by clamps. Further welding teams began working on the next ring of plates shortly after this photograph was taken. In the background, an X-ray unit stands ready inside the bowl for weld examination.

A welder works from the bottom centre of the reac tor vessel, welding together the 3in. thick 'petal' plates which form the lower bowl. Accurate edge preparation of the plates has been achieved by a specially developed flame planing technique in John Thompson's works. The temperature of the weld area is maintained between welding runs by means of flame torches, one of which is seen ready to hand, in front of the welder.



Buttercups at Berkeley..

John Thompson's construction men — familiar in their yellow helmets on power station and industrial sites throughout Britain — are now at work on the Central Electricity Authority's first commercial nuclear power station being built by the A.E.I. — John Thompson Nuclear Energy Company at Berkeley, Gloucestershire. Crisply, the construction programme proceeds to a minutely planned schedule. The bottom dome portion of one of the huge 1,000 ton reactor vessels was transported in sections to the site where it is being welded together to grow simultaneously with the reactor building. The "Buttercups" are speedily getting on with this job in which they are building the reactor vessels, the thermal shielding, the sixteen large heat exchange towers, gas ducting and nuclear fuel loading machines.



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THE BLUE PAGES

A QUICK GLANCE AT THE LATEST TECHNICAL DEVELOPMENTS THROUGHOUT THE WORLD

● *VACUUM STREAM DEGASSING OF MOLTEN STEEL*

It has been announced that equipment for the vacuum-stream degassing of steel on a commercial scale has now been developed. This equipment degasses the steel during the pouring of the ingot by directing the stream of molten metal just tapped from the open-hearth or the electric melting furnace into a pre-evacuated vacuum chamber which houses the ingot mould, the vacuum employed being of the order of 150 microns. Obviously, the greater the exposure of surface area of the liquid metal to the vacuum, the greater is the degree of refinement achieved. In the new process the molten material is turned into a fine shower or spray of droplets as it passes from the ladle into the vacuum chamber. The steel is tapped from the furnace into a transfer ladle which carries it to the degassing chamber, where it is poured into an intermediate ladle which is kept full from the transfer ladle, the vacuum chamber itself having previously been pumped down to a high vacuum. An aluminium diaphragm seals the opening of the chamber from an antechamber located above the vacuum chamber. When the intermediate ladle is placed upon the antechamber, a by-pass valve to the vacuum pumping system is opened, so that the antechamber is also evacuated. To start the pour, the stopper rod in the intermediate ladle is opened and the liquid steel flows through the bottom nozzle, the stream puncturing the aluminium diaphragm and entering the large vacuum chamber. The sudden pressure drop causes the molten metal to break up into a spray of finely divided molten particles which are caught in a conventional ingot mould resting on the bottom of the chamber.

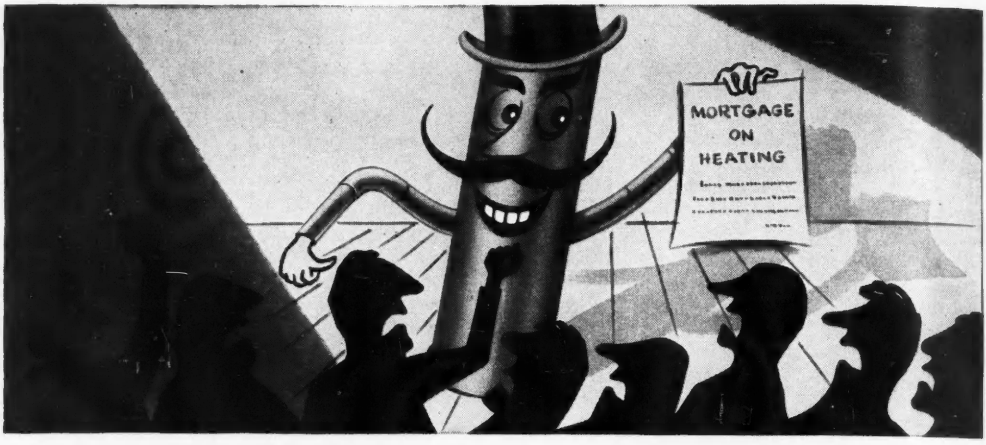
● *HEAT-RESISTANT CERAMIC COATINGS FOR ALUMINIUM*

New heat-resistant ceramic coatings for the protection of aluminium have been developed, and it is reported that, when applied in a thickness of 0·0015 in., they will protect aluminium and its alloys from temperatures up to 1800°F, i.e., from a temperature which would melt a hole in an unprotected sheet in as little as 30 sec. While their actual composition is not given, it is stated that these coatings contain (1) a low-melting glass, either of a commercial type or a high-lithia frit type for coatings to be applied to low-melting alloys, such as aluminium, (2) refractory additives, such as titania, zirconia, magnesia, or silica, and (3) a fluxing agent, lithium compounds being preferred for this purpose. It is claimed that these coatings have a high degree of adherence to the base metal and withstand impact shock, flame impingement, thermal shock, and endurance tests. The coatings may also be applied to steels which have previously been aluminized. A disadvantage is their limited corrosion resistance and surface hardness, and, where corrosion resistance is required, a special corrosion-resistant coating must be applied on top of the ceramic coating.

● *CERAMIC CATALYST COATING FOR IMPROVING THE PERFORMANCE OF INTERNAL COMBUSTION ENGINES*

A catalytic ceramic coating for the piston-heads of internal combustion engines has been developed and may significantly reduce carbon monoxide and unburned hydrocarbons in the exhaust. The coating is also reported to offer promise of thermal insulation, greater combustion efficiency, and more economical engine operation. This development is said to have its origin in earlier research concerned with flame ceramics which indicated that ceramic coatings might reduce thermal cracking and carbon in diesel engines. This has resulted in the development of a flame-sprayable ceramic coating containing rare-earth oxides which act as a catalyst in internal combustion engines. In a laboratory test, about 50% of the top area of the pistons of a standard automobile engine was coated, and the engine was then run under idling, cruising, full acceleration, and deceleration conditions with non-leaded petrol and with air bled in at the carburettor intake. Comparison of the exhaust analysis obtained in this test with that of an identical but " uncoated " engine revealed that the coating led to a decrease in carbon monoxide and unburned hydrocarbon content, especially for conditions of acceleration and deceleration. The report states that, while the coating may significantly affect engine exhaust, research is

We extend to all readers our best wishes for a Happy Christmas and a Prosperous New Year



I WAS THE VILLAIN

—HOT WATER PIPE HISSES

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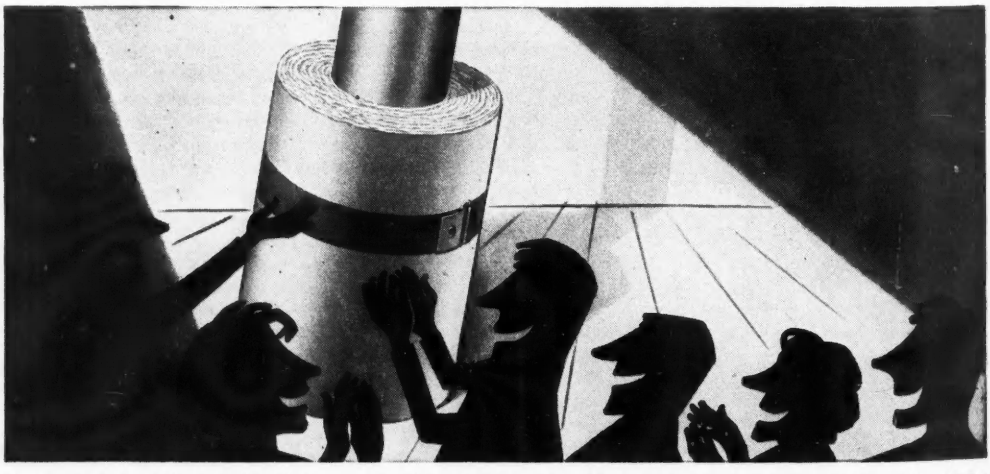

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now directed towards the development of a more active and stable coating material to be used for tests on diesel and petrol engines using leaded fuels. It is interesting to note that this development follows closely on the discovery by other research workers of a promising oxidation catalyst for similar purposes. In this case scandium pentoxide was found to eliminate effectively more than 80% of noxious hydrocarbons from the exhaust of a single-cylinder engine. Vanadium pentoxide was also investigated with success. As a practical application, the use of a container with vanadium pentoxide located near the engine can be visualized.

● *SCARFING TORCH*

The design of a recently developed three-hose scarfing torch aims at the solution of problems encountered in carrying out heavy-duty work where large rates of metal removal are desired. The new torch, which is claimed to have successfully passed operational tests in practice, permits independent control of preheating- and scarfing-oxygen flows. It thus removes the difficulties arising with conventional torches, which permit sudden changes in preheat flow and altered oxygen/acetylene ratio when the main scarfing stream is suddenly started or stopped. In removing seams, scabs, cracks, or laps from billets, ingots, or slabs, stability of the flow of oxygen for combustion, irrespective of oxygen for scarfing, becomes important. Scarfing-oxygen pressure in any torch is generally five to seven times the pressure of the preheat oxygen. Maintenance of preheat flow, despite such violent changes in scarfing-oxygen flow during torch use, has hitherto been ignored or has been accomplished through complicated valving and regulating devices in the torch. Such mechanisms increase torch maintenance and, even when operating perfectly, can only approximate the absolute independence of oxygen flows which is inherent in three-hose design. In the new torch, the independence of the two oxygen flows is maintained all the way back to independent pressure regulators. Additional features are an improved removable guard over the head of the torch and an improved skid-ring on the end of the tip.

● *CONTINUOUS CONVERSION OF PIG-IRON INTO STEEL*

Many methods and apparatus are known for the conversion of a continuous stream of pig-iron to steel by blowing gaseous refining media onto or into such a stream, and it is a common feature of all these methods that the direction of flow of the pig-iron stream should be horizontal or slightly inclined. In order to control correctly the reactions which then take place, one after the other or simultaneously, it has often been proposed to provide reaction compartments which can be charged with slags of different composition, or to charge the reaction slag so that it flows in countercurrent to the pig-iron, the object being to ensure that the fresh highly reactive slag comes into contact with, and acts upon, the already partly refined metal. A recent patent specification points out that all these proposals create difficulties in providing the requisite conditions between the iron and the slag, i.e., as regards reaction time and contact between metal and slag for carrying out the reaction. It is claimed that it is possible, when using a gaseous refining medium, to allow all the refining actions, e.g., not only decarburization and dephosphorization, but also slagging of the silicon and manganese, to proceed simultaneously and completely. The apparatus proposed for the continuous conversion of pig-iron into steel by blowing on oxygen-containing refining gas consists of a container which at the top is provided with a water-cooled nozzle, through which the gas is introduced into the contents of the container. Provision is also made to feed slag-forming material continuously or intermittently to the surface of the molten bath. The refining gas may be oxygen, air, carbon dioxide, or water, either separately or in any desired mixture.

● *IMPROVED METHOD OF PRODUCTION OF ARTICLES MADE FROM ALUMINIUM NITRIDE*

With its great hardness, high melting point, chemical inertness, good thermal conductivity, and poor electrical conductivity, aluminium nitride is of definite industrial value as a refractory or abrasive material. However, attempts to produce articles of aluminium nitride have hitherto, for one reason or another, been unsuccessful or uneconomical. It is therefore of interest to note that a recent patent describes a process for the commercially economical production of articles composed mainly of aluminium nitride and substantially possessing the same properties as aluminium nitride itself. Basically, the method of production of such articles comprises intimate mixing of powdered aluminium nitride with a particle size of not more than 1 mm, a minor proportion of one or more powdered metals of groups III, IV, or V of the periodic classification (e.g., aluminium, silicon, titanium, or vanadium) with a particle size of not more than 1 mm, a non-aqueous binder (e.g., paraffin wax, ceresine, or polyglycols), capable of increasing the compactness of the mixture on moulding and of being completely removed after moulding, and a non-aqueous solvent for the binder (e.g., trichloroethylene). The solvent is then removed from the intimate mixture, which is subsequently moulded into the desired shape under pressure and heated at a

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0— 250 V.	
0— 1000 V.	

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temperature above 500°C in a nitriding atmosphere substantially free from oxidizing gases and gaseous carbides, out of contact with carbon. The proportion of metal to aluminium nitride in the initial mixture is such that the article obtained after firing has a higher compactness than the mixture after moulding. It is stated that the articles obtained by the process show no irreversible variation in volume not only after firing but also after long storage in cold air. These articles may be employed for all refractory purposes, e.g., as furnace linings, muffles, crucibles, burners, and diffusers, even under reducing conditions; they are also suitable for all abrasive purposes, e.g., as grinding wheels, buffing stones, wire-drawing dies, and thread guides, and also for combined abrasive and refractory purposes.

● *DUCTILE CERAMIC MATERIALS*

Usual ceramic materials are well known to lack ductility and, in order to obtain a material which has some of the properties of a ceramic combined with some ductility, heterogeneous metal-ceramic mixtures, i.e., cermets, have been developed. The production of such materials includes the heating of intimate mixtures of a metal of high melting point and a ceramic material to the sintering temperature, but this process does not give a product with a continuous distribution of the metal phase, while processes depending on the impregnation of ceramic by metal are not always effective and are difficult to carry out with metals of high melting point. A recent invention is based on the observation that metal-ceramic distribution may be effected by the splitting up of a chemical sub-compound or solid solution on cooling into metallic and non-metallic phases. The proposed method consists of the use of a mixture composed essentially of a refractory compound of a metal and the metal in finely divided condition. This mixture is heated to a high temperature in an inert atmosphere or in vacuum and then cooled. The proportions of the compound and the metal in the mixture are chosen in such a way that a solid solution formed by the heating is split by cooling into a metallic and a non-metallic phase.

● *HIGH-TEMPERATURE BUTYL RUBBER*

It is reported that extensive studies in the compounding and vulcanization of butyl rubber have resulted in the production of a new composition which is notable for its high-temperature characteristics. Compared with ordinary butyl rubbers, the new material has excellent dry-heat resistance, and peak operating temperatures as high as 450°F can be tolerated. The percentage of permanent compressive deformation is extremely low, and at 300°F amounts to approximately 25% that of straight butyl rubber. With regard to chemical resistance, it is claimed that the new rubber has a maximum nitric-acid resistance of 50% for sustained use at 150°F, as compared with 30% for ordinary butyl. As concerns ageing characteristics at high temperature, the new composition is said to show excellent stability, and in one case withstood superheated steam at 450°F for one month, as compared with two days for conventional materials. However, saturated steam will cause all butyl rubbers to swell and break down. Under compressive loads the new compound compares very favourably with conventional rubber compounds. Low compression set is, of course, an important feature in such moulded parts as gaskets, O-rings, and vibration mountings, especially where temperature is a factor. Against those chemicals calling for the use of butyl rubber, particularly the oxidizing compounds, the new material has somewhat improved resistance. Like all butyl rubbers, however, it is attacked by certain solvents, and in such cases the chlorosulphonated polyethylenes and the polychloroprenes should be used. Ozone resistance has been improved, and this is important where use out of doors or in the vicinity of electrical equipment is concerned.

● *NEW STAINLESS STEEL FOR HIGH-SPEED AIRCRAFT AND MISSILES*

According to a recent announcement, a new type of precipitation-hardening stainless steel with high strength/temperature properties has been evolved. This material is intended for the skins and structural parts of aircraft flying at speeds of Mach 4, where the material may be exposed to temperatures as high as 1000°F. It is of special interest to note that the new steel, which contains 15% Cr, 7% Ni, 1·2% Al, and about 2·5% Mo, has a cost of only 10% that of high-strength titanium alloys. Its high-strength properties are due to the strong precipitation-hardening reaction caused by its aluminium content, while its molybdenum content confers good retention of these high-strength properties up to 1000°F. The carbon content of the steel is controlled below 0·09%, permitting it to be welded without the preheating or post-annealing treatments necessary to minimize cracking when welding high-strength martensitic carbon and stainless steels. In the annealed condition, the steel has a predominantly austenitic grain structure, which, it is claimed, makes it easier to form than other high-strength materials ; also it does not temper or deteriorate in room-temperature strength after exposure for long periods at 400 to 900°F. A slight increase in room-temperature strength has been measured after the steel has been stressed above operating limits for 1000 hr at 800°F. Procedures for hardening may be varied to suit different production cases ; thus,

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for instance, when severe cold forming is necessary, annealed material with an ultimate tensile strength of 130,000 psi is used, precipitation hardening after transformation treatment being effected by heating at 1050°F. for 1½ hr and then cooling in air.

• *DETECTION OF IMPURITIES IN RARE GASES*

Commerically produced rare gases are often contaminated by small quantities of gaseous impurities. For example, the rare gases in air, i.e., argon, kryton, and xenon, are frequently contaminated by small amounts of nitrogen. For many uses the presence of minor amounts of impurities is not harmful, but in certain applications the rare gas is required in a high state of purity. For example, argon intended for use in gas-shielded arc welding must have a relatively low nitrogen content, and similarly there is a definite upper limit to the amount of methane tolerable in helium intended for use as a shielding gas. The rare gases are inert, and where the contaminant is also relatively inert, as in the case of nitrogen, only those methods based on physical effects are likely to be practicable for the estimation of the contaminant. An apparatus has been patented which utilizes the effect of traces of impurities on the optical characteristics of a silent electric discharge in the rare gas at low pressure. In the case of pure argon, the discharge is blue, but the addition of nitrogen introduces a tinge of pink. This phenomenon can be used as the basis of a quantitative estimation of the impurities contained in a rare gas. The apparatus used for this purpose comprises an electric discharge tube, through which the impure rare gas is passed at substantially subatmospheric pressure, and one or more photoelectric cells responsive to the changes in the optical characteristics of the discharge due to the impurity. Another set of photoelectric cells is provided which is responsive to the optical characteristics of the discharge when pure gas is passed through the discharge tube, but not to changes due to gas impurities. The two sets of cells are connected in opposition, so that an indication of the amount of impurities contained in the gas is obtained.

• *COMBINED SPINNING AND FORGING MACHINE*

By combining the features of a vertical spinning lathe with a process for forging the wall thickness of sheet parts, a new machine not only makes it possible to form conical, hemispherical, parabolic, and other shapes from a single piece but also to forge the metal, varying the wall thickness from an inch down to a few thousandths of an inch. Two hydraulically operated opposed rollers are used to supply the force required for spinning and forging. These rollers feed vertically down the form longitudinally into die contours and, as they are mounted on angular tilting heads, follow all contours, maintaining a 90-deg. contact with the surface of the work. Each roller operates independently of the other, and roller travel in all directions is tracer-controlled from templates. A forming force of 225,000 lb is supplied to each roller by hydraulic cylinders operating at 3000 psi, the feed rate being 60 ipm. The die, which is contoured to the shape of the finished part, is mounted on a rotating table with spindle speeds up to 400 rpm. The system includes a closed television circuit for close-up vision from a remote location, providing safety for personnel in the event of failure of parts. Other circuits permit programming forming operations for automatic duplication of parts. One of the basic machines of this type is designed for forming thin-walled parts for uniform wall thickness, e.g., tank ends, missile noses, and aircraft fuselage components, but different models may be developed for other industries.

• *SEMICONDUCTORS FOR MEASUREMENTS OF MAGNETIC FIELDS*

For measuring magnetic field strength, the dependence of the specific electric resistance of bismuth on a magnetic field is generally employed, using long bismuth wires wound into flat coils and capable of insertion into narrow air gaps. However, a disadvantage of bismuth coils is that only relatively low measurement values are obtained. Another method of magnetic field measurement utilizes the Hall effect, in which flat strips of crystalline germanium are secured to small probes consisting of a handle and a thin flat holder. It is also possible to employ a quartz plate as the holder and to apply on it a germanium layer by vapour coating. A recent proposal in a patent specification is the use of semiconducting compounds of high carrier mobility, i.e., higher than 6000 cm^2/volt-sec. Compounds of this type contain aluminium, gallium, or indium, with phosphorus, arsenic, or antimony, the choice of the substance used preferably depending on the effect to be utilized. Thus, if the dependence of the specific electrical resistance on the magnetic field is required, semiconducting compounds with a large specific resistance change should be used, e.g., indium antimonide. On the other hand, for utilizing the Hall effect, resistance elements consisting of indium arsenide are proposed, because this substance combines a particularly low temperature dependence of its specific resistance and of its Hall constant. The use of these types of semiconductors is claimed to present special advantages in cases where magnetic fields which vary as a function of time are to be measured, since they are not subject to the disturbing influence of the inductive component.

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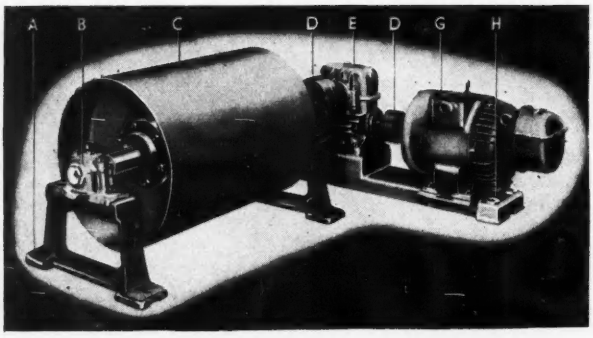

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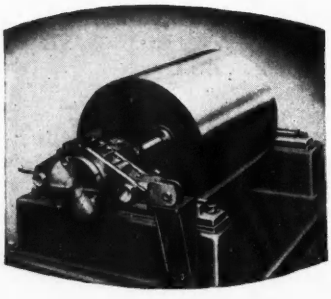

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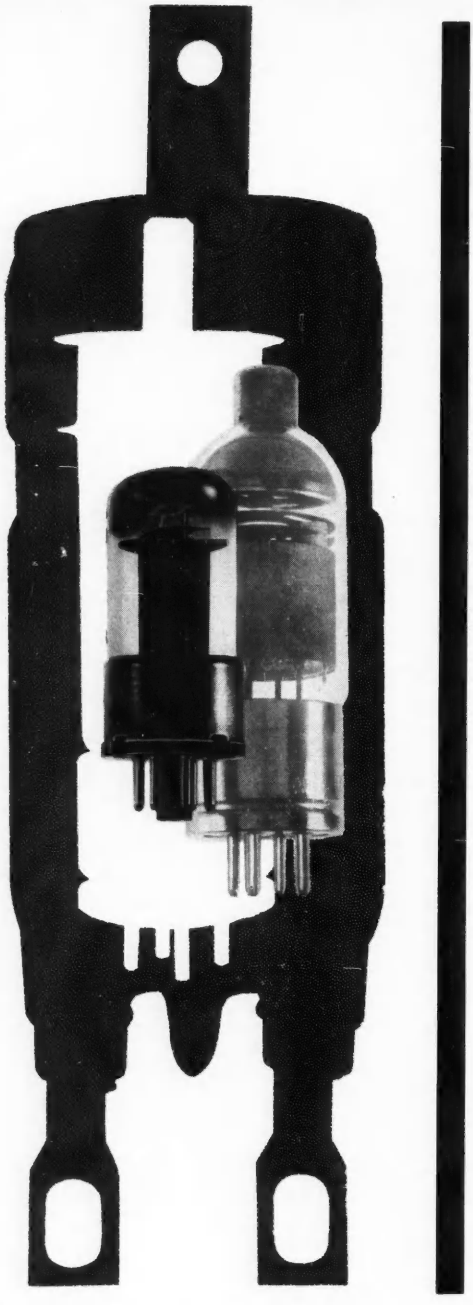
ENGINEERS' DIGEST SURVEY No. 3

Electrical Variable-Speed Drives

BY

E. R. Laithwaite, Ph.D., M.Sc., A.I.E.E.

Motor speed contr ol



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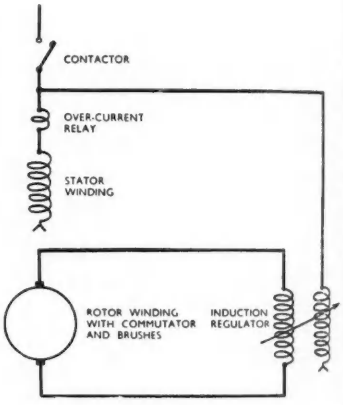

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Electrical Variable-Speed Drives

By E. R. Laithwaite, Ph.D., M.Sc., A.I.E.E.*

Wherever the demand for an electrical variable-speed drive arises, there is a wide range of machines from which to choose, but there is no one type of machine which provides the ideal drive for all requirements. It is possible that for any given set of circumstances there may be a type of drive which is ideally suited to the job in question but, in general, the engineer will find himself faced with a compromise. One type of machine may offer advantages in certain respects, while another will be found to be better in others, and the engineer must decide finally what he is prepared to sacrifice on the one hand in order to gain on the other. The object of this survey is to provide sufficient discussion of the mode of operation and salient properties of the majority of electrical variable-speed drives to enable an evaluation of their relative advantages and disadvantages to be made, and so to choose the most suitable system for a particular application.

The field covered by this subject is so wide that it is almost impossible to make a list of all the requirements which may arise in one application or another. In order, therefore, to provide some limitation to the length of this survey, discussion of electrical servo-mechanisms such as the Velodyne is omitted, although brief reference will be made from time to time to servo-systems, when it is felt that benefits may accrue from further investigation into the use of a servo-mechanism to meet a particular requirement. Similarly, no details are given of such ancillary equipment as switchgear, starters, and resistors, as these constitute a subject in themselves.

The following list contains some of the principal factors to be considered when choosing an electrical variable-speed drive, the first five factors being perhaps the most general.

Principal Factors Affecting Choice of Drive

(a) First Cost.
(b) Efficiency.
(c) Speed Range.
(d) Regulation.
(e) Power-to-Weight Ratio.
(f) Availability of Supply.
(g) Maintenance and Reliability.
(h) Change in Power and Torque over the Speed Range.
(i) Simplicity of Control Gear.
(j) Effect of Variations in Supply.
(k) Power Factor.
(l) Characteristics of the Load.
(m) Operational Environment.
(n) Braking Requirements.

There is no significance in the order of the items in the above list. For example, there may well be applications where first cost and running cost are of no consequence, provided that the end is achieved. There may even be examples where the entire list may be superseded by a requirement which is not even included. It is hoped, however, that the subsequent descriptions of the various systems available will form sufficient basis for a decision to be made in all cases as to which system offers the best solution. Incidentally, a large proportion of the factors in the list also applies to mechanical and hydraulic drives.

* Electrical Engineering Laboratories, Manchester University.

(a) First Cost

Many of the items in the above list have a major influence on the first cost of a variable-speed drive. In general, the greater the speed range demanded, the higher the price, some systems being better than others in this respect. In some applications the assessment of first cost must extend well beyond the motor itself to such considerations as the cost of the control gear, the cost of mounting the machine in the required position, and the cost of any additional equipment made necessary through sacrificing one aspect in order to obtain better performance in another. The power-to-weight ratio clearly has a bearing on the cost of mounting, whilst the extra cost of providing a type of supply not readily available must also be considered. In general, first cost is probably more important than running cost.

(b) Efficiency

Efficiency is generally the major factor affecting running costs. Electrical machines are generally very efficient, provided that they are not very small. For example, most electrical machines over 2 hp are more than 60% efficient, and efficiency is therefore often only a secondary consideration in choosing an electrical variable-speed drive. It must nevertheless be remembered that, if two or three machines are employed in a system, the product of the individual machine efficiencies may well result in a rather poor overall efficiency. Another aspect of poor efficiency which may be important is that all the losses appear as heat, which must be continuously removed. With regard to fractional-horsepower motors, the inherent low efficiency is never likely to present a problem, unless the number of motors required becomes very large, as the amount of power wasted is trivial.

(c) Speed Range

Speed range is quite a potent factor in that it can influence other quantities, such as power-to-weight ratio power factor, and, of course, first cost, to a very large extent, particularly if the speed range demanded is high. Consequently, a compromise may often be the best choice. For example, to face a disc on a lathe and maintain a constant cutting speed from a radius of 12 to ½ in. requires a 24 : 1 continuously variable speed drive. The resulting size, complexity, and cost of such a machine are such that the designer is well advised to be content with a much lower speed range and to tolerate small deviations from the ideal cutting speed over a comparatively small area of the disc. Rarely are the efficiency and regulation values maintained over the entire speed range of any machine, and, as a general rule, the greater the speed range, the greater is the variation in these quantities. The power-to-weight ratio is also likely to be severely affected, usually falling towards the low-speed end of the range.

(d) Speed Regulation

A general rule concerning speed regulation is that the more strictly the machine is expected to hold any demanded speed against a variable load, the higher will be

the penalty in some form or other, i.e., if not in actual cost, in loss of power-to-weight ratio, efficiency, etc. There are, of course, applications where speed fluctuations must be virtually zero, and such applications usually call for the use of a servo-controlled system. The effect of a high speed range, as already mentioned, should also be borne in mind.

(e) Power-to-Weight Ratio

Power-to-weight ratio is naturally significant in that it influences first cost. It has other important aspects, however, inasmuch as certain applications demand as small a weight as possible, irrespective of cost, e.g., in the motors used in aircraft. Often, " power-to-size " ratio may be more important than power-to-weight ratio. In some applications, the choice of variable-speed equipment with a total weight and size exceeding those of another system is preferable, provided that the final drive motor is the smallest possible. An example of the latter is found by comparing a Schrage motor with a Ward-Leonard set with an induction-motor drive. The total weight of all three machines of the Ward-Leonard set exceeds that of the Schrage motor, but the volume and weight of the final d.c. motor of the Ward-Leonard set is much less. Thus, it may be necessary to distinguish between overall power-to-weight ratio and power-to-weight ratio " at the job ".

(f) Availability of Supply

The British grid system, providing a 3-phase, 4-wire a.c. supply, is naturally the most common source. In a number of variable-speed systems a d.c. motor is used as the final drive, and some form of converter is needed in addition to the motor. It does not follow, however, that, if a d.c. source of supply were readily available, a simple d.c. motor would in all cases be the best solution. The efficiency and accuracy of the control equipment and the working environment may well favour the use of a more complex system.

(g) Maintenance and Reliability

There is no doubt that for robustness, simplicity, and reliability the induction motor would undoubtedly be the natural choice, were it not for the fact that the simple cylinder of almost solid metal which constitutes its rotor results in a virtually constant-speed motor. Furthermore, when the simple induction motor is modified by fitting a wound rotor with a commutator, maintenance troubles associated with the commutator and brushgear inevitably result. The problem of commutation is most acute in a.c. machines, particularly in single-phase types, while d.c. machines suffer less in this respect from brush wear and the consequences of sparking. Machines incorporating only slip-rings and brushes are generally less troublesome in this way, although a motor with brushgear of any kind will require more maintenance than a brushless motor.

(h) Change in Power and Torque over the Speed Range

For a fixed-speed machine, such as an induction motor, the speed-torque curve can be shaped in the design stage to give a wide variety of characteristics, and such quantities as overload torque, starting torque, and speed regulation on full load can be specified by the customer. In the case of variable-speed motors, however, the complete speed-torque curve can rarely be fixed by design to meet requirements for more than one particular control setting. It may therefore be necessary to decide whether to accept the performance at another setting, or to install a larger machine than might at first appear necessary, in order to comply with minimum requirements at all control settings. The power output from many electrical variable-speed drives increases with speed, these being, in fact, *constant-torque* systems. At the same time, other systems have inherently *constant-power* characteristics, torque decreasing with an increase in speed. Some systems have characteristics which embody neither constant power nor constant torque, but lie somewhere between the two. Very often the materials in a variable-speed motor are used efficiently only at one particular control setting, i.e., at one required speed. At any other speed setting, the materials may not be utilized to the full, and the power-to-weight ratio will suffer accordingly. The characteristics of the load, to be discussed later, must also play a large part in determining the type of motor most suitable in many cases.

(i) Simplicity of Control Gear

This aspect is closely allied to maintenance and reliability. On the whole, the simpler the control, the less will be the maintenance required and the more reliable the equipment. Electronically controlled motors must usually possess some special features over and above the simpler types of control before their use is justified. Thus, for example, although electronic control gear can provide effective speed regulation on all loads down to zero over a wide range of speed requirements for a d.c. motor, if such requirements are exacting, the result may well be a controlling device bigger than the motor itself and certainly requiring more maintenance.

(j) Effect of Variations in Supply

For general-purpose drives, a small percentage variation in supply voltage or in frequency may not have a very profound effect. For some purposes, however, the results of such fluctuations may be vital. A study of the characteristics of the various systems will generally reveal the result of supply changes and, if the effects are likely to be devastating, a servo-mechanism is usually required, either to control the supply itself or to counteract the effect of the fluctuations through the medium of the control gear. Some variable-speed drives are less sensitive to variations than others, and for applications where the effects are quite important, but not vital, there is generally a suitable system available.

(k) Power Factor

Low power factor alone is never an insoluble problem in alternating-current drives. At worst, supplementary equipment for correcting power factor can be installed, thereby increasing the cost of the installation. The penalty for consumption of large quantities of heavily lagging current is reflected in higher running costs.

The ordinary induction motor always takes lagging current, and the problem of low power factor in variable-speed a.c. motors is usually no worse than that for fixed-speed a.c. motors ; in fact, the variable-speed motor is often the better in this respect. As a rule, power factor varies both with load and control setting.

(l) Characteristics of the Load

Under this heading should be considered such factors as requirements for the machine to start up under load, steady or intermittent loads, and required rate of acceleration or deceleration from one speed to another.

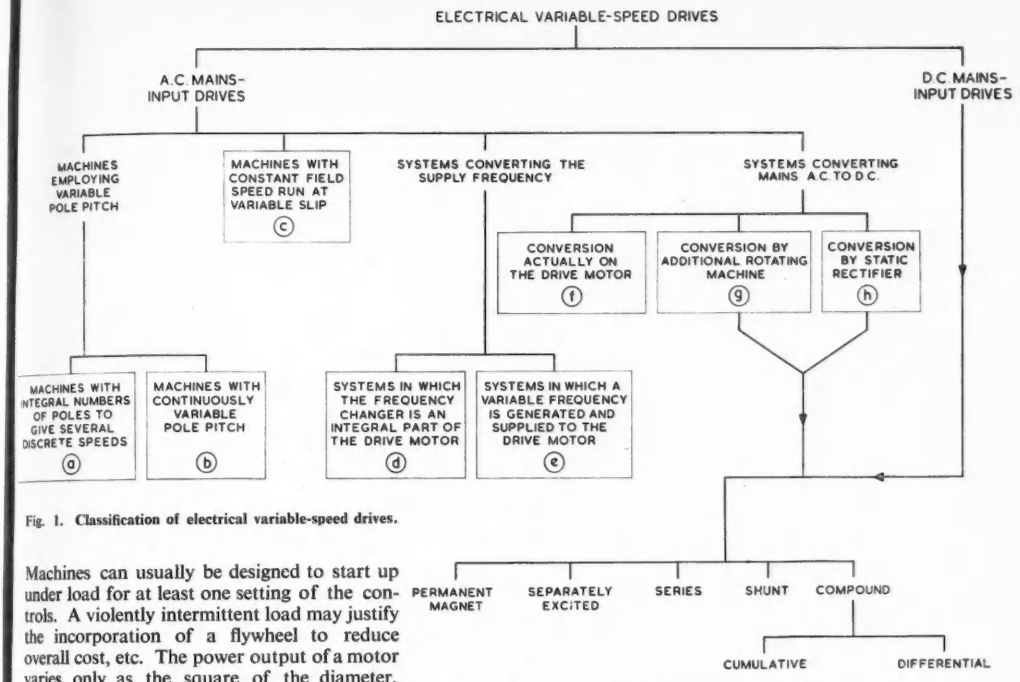


Fig. 1. **Classification of electrical variable-speed drives.**

Machines can usually be designed to start up under load for at least one setting of the controls. A violently intermittent load may justify the incorporation of a flywheel to reduce overall cost, etc. The power output of a motor varies only as the square of the diameter, whereas the rotor moment of inertia varies as the fifth power of the diameter. Motors designed for rapid changes in speed are therefore usually of small diameter and of comparatively great length.

Certain types of loads, particularly those in which fluid friction is involved, e.g., fans, have a rapidly rising torque-speed characteristic. The choice of a motor possessing a rising characteristic is therefore unwise for this type of load, as it may easily fail to reach the desired full-load speed, owing to the existence of a stable condition at a much lower speed.

(m) Operational Environment

Operational environment often rules out the use of commutator motors or even slip-ring motors. Explosive atmospheres naturally do not permit the possibility of sparking, whilst corrosive atmospheres so quickly destroy the surfaces of commutators and slip-rings as to make their use impracticable. Brush wear in motors operating in low-pressure atmospheres is excessive. Motors for use in high-vacuum work need special design to reduce outgassing of insulating materials, etc.

For some applications it is possible to use a variable-speed system employing more than one machine, where only the final drive motor is brushless, the control gear and auxiliary equipment being housed outside the prohibitive atmosphere. Other applications merely demand that a motor be flameproof, in which case a commutator motor operating on a closed air-cooling circuit can be used. Other fairly common requirements are that the motor should be able to withstand heavy spraying with water or high humidity, or that it be merely splash-proof or drip-proof.

Motors required to work in high temperatures also need special design. In this connection some motors take in "cooling air" at 100°C, and the use of special insulating materials is the main consideration in the design of such machines.

In all cases of unusual environment, there is some price to be paid for special design. Thus, the machine may be larger than the conventional type for the same power, or may require a special shape. In either case, it will be more expensive.

(n) Braking Requirements

Braking requirements are very often based on personnel safety measures. Some types of machine readily lend themselves to what is called "dynamic" braking, i.e., they can be used to stop themselves rapidly, either with or without the assistance of a mechanical brake, usually necessitating additional control gear and in some cases auxiliary current supplies. In very large motors the main problem in stopping may be simply the disposal of the energy stored in the rotor. In certain types of drive it is possible to arrange braking in such a way that the stored energy in the rotor is returned to the supply as the motor is decelerated. Such a machine is said to be capable of regenerative braking.

Types of Electrical Variable-Speed Drives

The operating principles of the various types of motor will now be described. Fig. 1 is a classification of electrical variable-speed drives under general headings, according to the principles employed, the first major division being made in terms of the type of input. The fact that the a.c. input side appears more heavily developed in this diagram is perhaps a direct result of the readily available a.c. grid supply.

For convenience, the electrical variable-speed drives described in the following pages have been divided into three main groups, i.e., a.c. drives, d.c. drives, and systems converting mains a.c. to d.c.

A.C. MAINS - INPUT DRIVES

Polyphase Induction Motors

Although a rigorous classical analysis of the operating conditions in a polyphase induction motor is extremely complex, the action can be described satisfactorily for most practical purposes by the analogy of the rotating magnetic field.

Conducting material placed in such a field is cut by the rotating field, the induced e.m.f. and current being in such a direction as to oppose the relative motion, i.e., the torque on the rotor attempts to accelerate it to the synchronous speed of the field. In the presence of a load torque T, whether it be used purely in acceleration, in true load, or in a combination of the two, the power delivered by the rotating field of speed ω_s to the rotor is $T\omega_s$. The torque exerted by the field on the rotor must equal the torque exerted by the rotor on the load. Thus, the power output is $T\omega$. The quantity $T\omega_s - T\omega$ must therefore be the rotor losses. The relative velocity between the rotor and the field, i.e., the angular velocity with which the rotor "slips" through the field, is $\omega_s - \omega$, and the fractional slip σ is defined as $(\omega_s - \omega)/\omega_s = 1 - (\omega/\omega_s)$.

The frequency of the e.m.f. generated in the rotor is therefore σf. Since $T\omega_s - T\omega$ = rotor losses, and $T\omega_s$ is the rotor input, the rotor efficiency is $1 - \sigma$.

The efficiency of the whole machine is, of course, less than this, and a reasonably designed machine might be expected to run at a small slip on full load. This being so, the frequency of the rotor e.m.f. is small, and rotor iron loss can be safely neglected in the simple theory, so that

$$\sigma = \frac{\text{rotor copper loss}}{\text{rotor input}} \quad .. \quad .. \quad (1)$$

This equation now forms a basis for the prediction of the speed-torque curve from given parameters. In this simple treatment, stator resistance, leakage reactance, and magnetizing current are ignored.

Suppose that the rotor is wound with a 3-phase winding like that of the stator, the turns ratio, rotor to stator, being N, and that the rotor resistance per phase is R and the leakage reactance per phase at standstill is X. At a slip σ, the rotor leakage reactance becomes σX. The induced rotor voltage per phase at standstill will be NE, if E volts per phase are supplied to the stator. At a slip σ, the rotor volts are reduced to σNE, and the rotor current per phase is $(\sigma NE)/\sqrt{R^2+\sigma^2X^2}$. The rotor copper loss per phase is therefore $(\sigma^2N^2E^2R)/(R^2+\sigma^2X^2)$, which is in watts if E is in volts and R and X in ohms. Hence, from eq. 1,

$$\sigma T\omega_s = \frac{\sigma^2N^2E^2R}{R^2+\sigma^2X^2} \quad .. \quad .. \quad .. \quad (2)$$

If the torque is to be expressed in lb-ft, then eq. (2) becomes

$$T = \frac{\sigma N^2E^2R}{\omega_s(R^2+\sigma^2X^2)} \frac{550}{746} \quad .. \quad .. \quad (3)$$

The shape of the torque-speed curve depends largely on the ratio R/X, and eq. (3) may be written

$$T = k \frac{a\sigma}{a^2+\sigma^2} \quad .. \quad .. \quad (4)$$

where $a = R/X$, and $k = \frac{N^2E^2}{\omega_sX} \frac{550}{746}$ (treating X as fixed and R as the variable parameter).

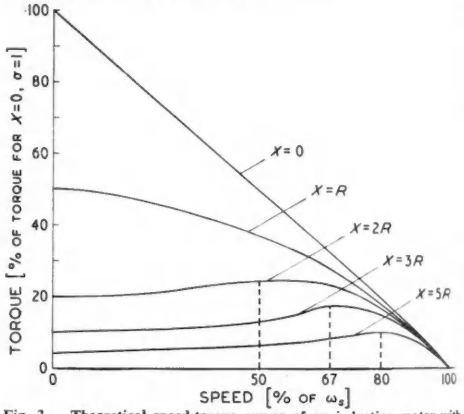


Fig. 3. **Theoretical speed-torque curves of an induction motor with variable leakage reactance X.**

Eq. (4) is plotted in Fig. 2 for various values of $a = R/X$. The peak of each curve occurs at a slip $\sigma = R/X$. Another way of analysing the effect of leakage reactance is to plot eq. (3) for fixed R and variable X, the results of such an analysis being shown in Fig. 3. Similar results can be obtained for squirrel-cage rotors and solid rotors of conducting material. Although the simple theory neglects stator leakage reactance and resistance, the latter quantities produce similar effects to their rotor counterparts. Increased stator leakage reactance, for example, means a greater reactive voltage drop, which is more and more potent with increased slip, since increased slip means increased current. Magnetizing current, too, has a similar effect to rotor leakage reactance on the speed-torque curve. Although leakage reactance is the result of an imperfection in the machine, it can nevertheless be exploited to produce desirable results.

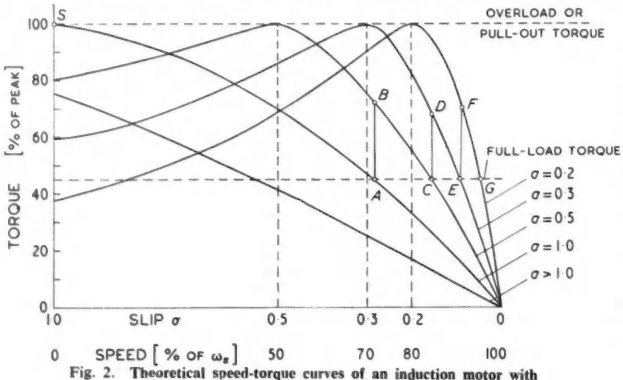


Fig. 2. **Theoretical speed-torque curves of an induction motor with variable rotor resistance R.**

Fig. 3 shows that, if it were possible to build a machine with no leakage, the starting torque would be many times the full-load torque. In fact, if full-load torque occurred at 5% slip, the starting torque would be 20 times full-load torque. The starting current, however, would also be far in excess of full-load current, and, indeed, would produce 20 times full-load stator copper loss. A certain amount of leakage reactance can therefore be useful in limiting starting current to a reasonable level, since it leaves the portion of the speed-torque curve between full load and running light virtually unimpaired. The loss of starting torque is generally a bad feature, however, especially in machines required to start up on load. This aspect is illustrated by the full-load torque line in Fig. 2. A machine normally run with a short-circuited rotor having an R/X ratio of 0·2 will not start up if the load torque exceeds 40% of the overload torque. The same figure, however, suggests the solution to the problem since, if the rotor resistance could be increased to, say, $R = X$, the whole of the overload torque would be available at starting. Once having run up to position A, the resistance can be reduced to give an R/X ratio of 0·5 (position B), and the machine will then accelerate to position C, more resistance being then removed, and so on, the machine reaching the normal running condition via the characteristics *SABCDEFG*. The penalty for this starting device is a wound rotor, slip-rings, brushes, and an external resistance—quite a high price to pay for the privilege of starting on load.

Double-Cage Rotors

Machines with wound rotors and starting resistance are now largely superseded by " direct-on start " double-cage rotor machines. The design of the double-cage rotor is a prime example of the exploitation of an imperfection, which once again is the leakage flux. The rotor

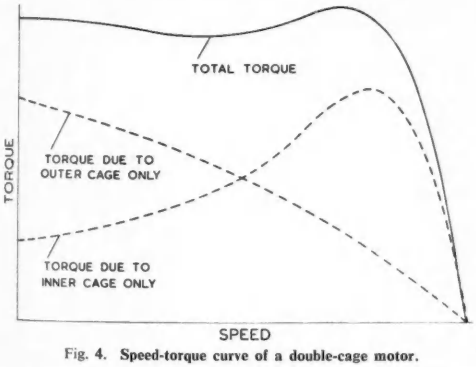


Fig. 4. **Speed-torque curve of a double-cage motor.**

carries two cages, one of thick bars sunk into the rotor in deep slots and the other of thinner bars in shallow slots. The inner cage has a high leakage reactance X and low resistance R, and the outer a low leakage reactance and comparatively high resistance. At standstill the impedance of the inner cage, largely due to its reactance, is greater than that of the outer, and the bulk of the current flows in the outer winding, which may be designed to have $R = X$. As the slip is reduced, the impedance of the inner cage falls appreciably, whilst the outer-cage impedance stays sensibly constant. If the slip is reduced to zero, the outer-cage impedance can only change by about 40%. The rotor current transfers to the inner cage as the machine accelerates, and, when running at normal slip, the inner cage carries the bulk of the current. The effect may be represented by the diagram in Fig. 4, where the effects of the two cages are shown separately, producing the flat characteristic for the whole machine. Many ingenious designs of double- and triple-cage rotors have been used to shape the speed-torque curve to meet particular requirements. In some cases, a deep rectangular bar is sufficient for the purpose.

Efficiency and Power Factor of Induction Motors

All electrical machines have one property in common with regard to their performance, i.e., the bigger the machine the better will be the performance over the same speed range. The dimensions which have the major effect on such quantities as power factor and efficiency are pole pitch, air-gap, and supply frequency. One method of assessing the properties of a machine is to calculate or measure the rotor relaxation time-constant τ. In terms of pole pitch p, rotor resistivity ρ, air-gap length g, and gap permeability μ_o, the time-constant τ is given by

$$\tau = 4p^2 \mu_o / \pi\rho g \quad .. \quad .. \quad .. \quad (5)$$

being much greater than $1/f$ in a good machine.

The pole-pitch term, which is the only term of second degree in the time-constant expression, plays an important part in the design of slow-speed machines. If an induction motor is to be run from a 50-cps supply at 100 rpm, it requires over 60 poles. Even on medium-sized machines, this entails a very small pole pitch, resulting in an efficiency and power factor which are of the same order as those for a 2-pole machine of only 1/30th the diameter. Generally speaking, a 50-cps machine with a synchronous speed in the 100- to 200-rpm region and of reasonable efficiency could be designed to supply much more power than that required. One line of approach in the design of slow-speed motors in the light of the above deductions is to build a large rotor, but to operate with just sufficient stator to give the desired power. This approach, which results in machines with discontinuous stators subtending arcs of less than 100 deg. at the centre, has been developed in Russia.[1]

Dynamic Braking of Induction Motors

Eqs. (2), (3), and (4) are valid for negative values of σ and for values greater than 1·0. A slip greater than 1·0 implies that the rotor is travelling in the opposite direction to the field, while negative slip means that the rotor is travelling faster than the synchronous speed of the field. The speed-torque curve of an induction motor plotted over the entire range of speeds from $-2\omega_s$ to $+2\omega_s$ is shown in Fig. 5. Although the simplified theory predicts a curve which is symmetrical about the speed ω_s, this is not realized in practice, and, owing to losses and magnetizing current which are not taken into account in the simple theory, T_m' is greater than T_m.

When the stator field of an induction motor is used to produce deceleration of the rotor, dynamic braking is said to be used. This may be effected in one of three ways, i.e., " plugging ", d.c. braking, and regenerative braking.

(a) " Plugging "

If two phases of the stator supply are interchanged whilst the machine is still running, the direction of motion

of the field is reversed and the machine, which was originally operating at a speed ω (Fig. 5), now finds itself operating at an effective speed of $-\omega$, and will be decelerated to rest under the influence of torque represented by ordinates of the curve *PA* in Fig. 5. It should be noted that, during this time, energy is being supplied to the machine, all of which is wasted as heat. Under this system the machine will not normally remain at rest, once it has been decelerated, and if the conditions remain unchanged the motor will be accelerated to a speed ω in the opposite direction.

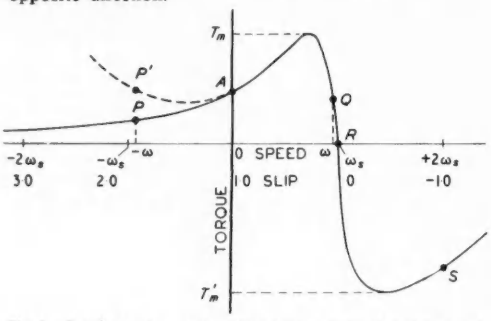


Fig. 5. **Speed-torque curve of an induction motor over the entire speed range.**

A third point to note in connection with plugging is that the available braking torque is small compared with the available accelerating torque, represented by ordinates from *A* to *Q*, and that the braking torque is least when the machine is first switched over to plugging. "Stray load loss"—an effect which is normally undesirable and which is produced mostly by pole face losses—tends to improve the operation of plugging by modifying the speed-torque curve for negative speeds to that shown dotted from *A* to *P'* in Fig. 5. Plugging is not, in general, a particularly advantageous method of dynamic braking.

(b) D.C. Braking

The second form of dynamic braking involves disconnecting the polyphase supply from the stator and reconnecting the windings to a source of direct current, so as to convert the stator into a system of static electromagnets. The machine is now the equivalent of a motor running at a speed $\omega_s - \omega$ which is being accelerated up to a speed ω_s; the braking torques are as shown in Fig. 6. These curves assume that the gap flux density produced by the direct current is the same as that produced by the alternating current in normal operation, but this is not quite the case in practice.

In this form of braking very little energy is supplied to the motor. There is some stator copper loss and energy is necessary to set up the steady flux, but otherwise there is

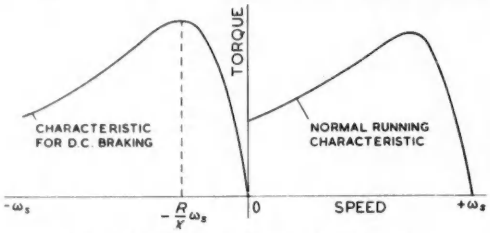


Fig. 6. **Dynamic d.c. braking of an induction motor.**

no need to supply power, as with plugging. The rotor kinetic energy, however, is dissipated as rotor copper loss, as in the case of plugging. Whilst it is true that there is no tendency for the machine to be re-accelerated in the opposite direction with this form of braking, a different disadvantage arises. This is evident from Fig. 6, which shows that there is zero braking torque at zero speed. Although the rotor is losing speed most rapidly at the velocity $-\omega_s R/X$, as shown in Fig. 6, the speed thereafter falls almost exponentially to zero and, in practice, the load and/or frictional forces are effectively the only braking forces over the last portion of the run-down.

(c) Regenerative Braking

Regenerative braking is the most economical method of the three. If the synchronous speed of the field can be lowered, the negative torque shown at *RS* in Fig. 5 will result, and the kinetic energy of the rotor will be returned to the supply as electrical energy, since the induction motor becomes an induction generator, once its speed exceeds that of synchronism. The disadvantage of this method is that it is necessary to reduce the field speed to zero in order to stop the machine. In general, regenerative braking is possible only between one speed and another, and not between any speed and rest.

Dynamic braking of induction motors may be summed up by saying that conditions are rarely very favourable for its use, and that, if the machine is to be brought rapidly to rest, mechanical brakes are necessary, whether or not dynamic braking be used to assist them. Finally, it should be emphasized that dynamic braking does not necessarily imply regenerative braking, and that plugging is a particularly uneconomical form of braking from the purely electrical point of view.

Speed Control of Induction Motors by Varying Slip

An induction motor with a wound rotor, slip-rings, and starting resistance can be used as a variable-speed device by inserting a rotor resistance when running and allowing the load torque to increase the slip. Thus, in Fig. 2 a motor designed to run at maximum speed at point *G* with no additional rotor resistance can be slowed down to the point *E* by adding resistance sufficient to make an R/X ratio of 0·3, instead of 0·2, assuming that load torque remains constant. If load torque falls off with speed, as in the case of fan drives, then the speed reduction from *G* to the curve *DE* would not be quite as great. The system is unsuited to constant-power drives where the load torque increases as the speed is reduced, since the system soon becomes unstable.

Variable slip-speed control systems are inherently inefficient, as a 2:1 reduction in speed implies a rotor efficiency of less than 50%, and this system is therefore an uneconomical proposition for all but very low speed ranges. In terms of eq. (1), the slip is increased by increasing the rotor copper loss, except that in this case a considerable proportion of the copper loss occurs not in the rotor itself, but in the external resistance. The second major disadvantage of the system is that, since the load forces the slip to the desired value, the speed of the motor is completely load-dependent.

An alternative method of varying the slip, which does not necessarily entail the use of slip-rings and a wound rotor, involves variation of supply voltage. Fig. 7 shows the variation in the speed-torque characteristic with changes in supply voltage. A constant load torque might

be supplied over the range of speeds from *A* to *B* without risk of instability. A fan-type load could be varied between *A* and *C*, whilst the speed range of a constant power load would be very small, e.g., between *A* and *D*. The penalty for this type of speed control is a variable-voltage source capable of handling the full stator current of the motor. Although the actual cost of such a piece of equipment may exceed the difference in cost between a squirrel-cage motor and a motor with a wound rotor, slip-rings, and external resistance, there is something to be gained in that the motor itself is brushless.

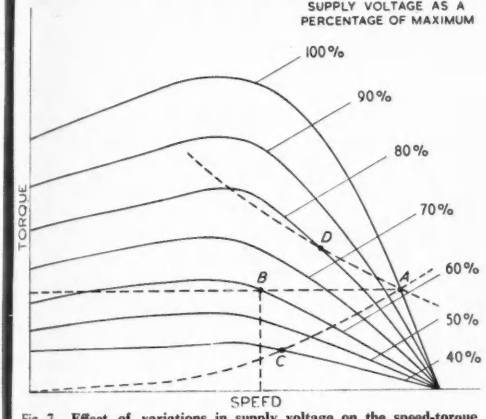


Fig. 7. **Effect of variations in supply voltage on the speed-torque characteristic of an induction motor.**

Despite its inherent inefficiency, the variable-slip type of drive has found many applications, both in small motors (where, as in the case of small d.c. motors, power consumption may be of secondary importance), and in very large projects such as pit winding gear (where the cost of the installation with this type of speed control is much less than with any other type of control system). An example is the winder installation at the Odendaalrus Gold Mine in the Orange Free State, South Africa. Four double-drum winders, each delivering 4200 hp, are in use, each winder being driven by two 2100-hp induction motors with a rotor resistance bank. A view of one of these winders, with its two motors (manufactured in the U.K. by The General Electric Co. Ltd.), is shown in Fig. 9. Incidentally, this installation utilizes d.c. dynamic braking, a 110-hp motor generator being used to supply the d.c. excitation to the stators for dynamic braking and being arranged for direct-to-line starting. This motor generator, with some of the associated control equipment, is illustrated in Fig. 8.

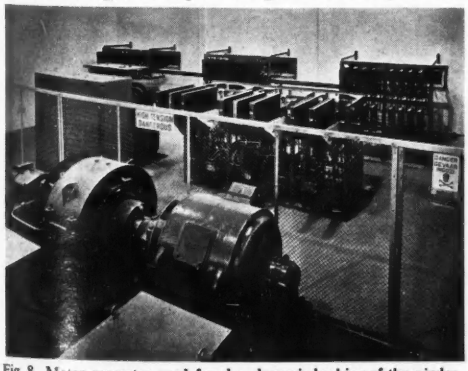


Fig. 8. **Motor-generator used for d.c. dynamic braking of the winder shown in Fig. 9, with some of the associated control equipment.** *(Courtesy of The General Electric Company Ltd.)*

An example of medium-sized drives of this type is provided by the Lawrence, Scott & Electromotors "Revcon" drive for cranes, in which the slip-ring rotor is specially wound for dynamic braking by d.c. injection.

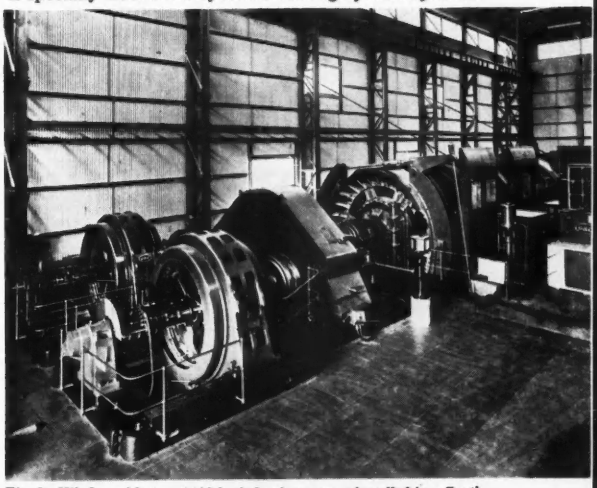


Fig. 9. **Winder with two 2100-hp induction motors installed in a South African gold mine.** *(Courtesy of The General Electric Company Ltd.)*

Slip-ring motors in a very wide range of sizes are manufactured all over the world. In comparison with drives incorporating commutator motors, the initial cost of a drive incorporating a slip-ring motor is very much smaller, and this is one of the main advantages of this type of drive, for which a wide range of control equipment, e.g., switchgear, starters, and speed controllers, is available from many manufacturers.

Drives Employing Eddy-Current Clutches

The varying-slip principle is often applied to an auxiliary device rather than to the prime mover. A system of permanent magnets may be carried on a spider and rotated near a conducting disc. Such a system is simply an induction motor in which the rotating field is produced by actual rotating magnets, instead of a set of static coils fed from a polyphase a.c. supply. Moreover, if the permanent magnets are replaced by electromagnets fed with direct current via slip-rings, variation in exciting current is equivalent to variation in supply voltage to a conventional induction motor, with a resulting variation in torque for a given slip. Such a variation is thus obtained by means of a simple control circuit which lends itself readily to remote electronic control.

In the application of such a system to a variable-speed drive, either the magnet system or the disc is driven by a standard constant-speed induction motor, the other member being then connected to the load. The main drive motor works at constant power, speed, power factor, and efficiency, provided that load torque is constant. The variable load speed is obtained simply by throwing away the extra power in the disc, and the efficiency of the clutch is always $(1-\sigma)$, as is the case with any induction device. The speed range is limited by the heat which can be dissipated in the disc.

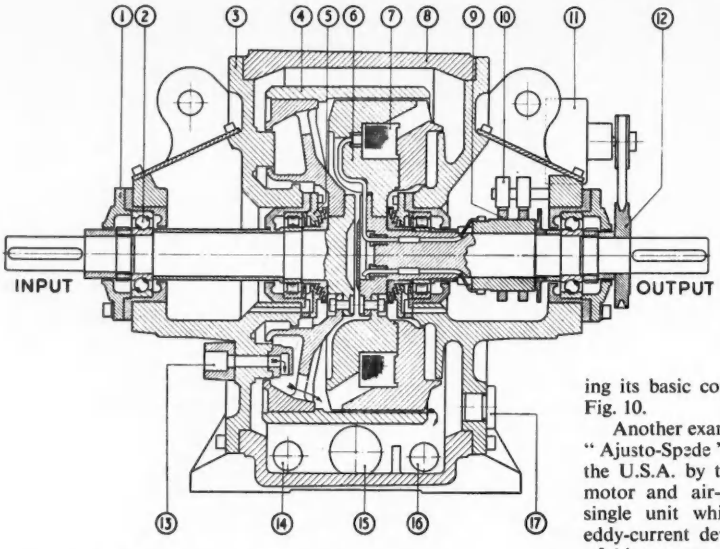


Fig. 10. Liquid-cooled "Heenan-Dynamatic" eddy-current coupling.

(1) Bearing cap.
(2) Anti-friction bearings.
(3) End cover.
(4) Armature assembly.
(5) Seals.
(6) Field assembly.
(7) Field coil.
(8) Centre casing.
(9) Slip-rings.
(10) Brush assembly.
(11) Governor generator.
(12) Pulley drive to generator.
(13) Liquid inlet nozzle.
(14) Bulb for liquid-proportioning valve.
(15) Main outlet.
(16) Liquid temperature switch.
(17) Air-gap inspection port.

(*Courtesy of Heenan & Froude Ltd.*)

Practical forms of eddy-current clutch often replace the disc by a cylinder containing the rotating magnets. Thus, in the "Heenan-Dynamatic" coupling, manufactured in the U.K. by Heenan & Froude Limited, the magnetic drag is obtained by providing one member with two rows of specially formed teeth, between which is wound a coil. Excitation of this coil by direct current sets up magnetic drag as soon as there is any rotation of one member relative to the other. By varying the amount of excitation, weak or strong drags can be created, output speed being regulated by control of excitation and drag. These couplings are normally excited by means of an electronic rectifier unit, the alternating current being rectified by the use of grid-controlled thyratrons, from which the d.c. output is modulated by means of the output from a small governor generator driven by the coupling output shaft. The output of this governor, the voltage of which varies directly with speed, is fed by a transformer and a separate metal rectifier to the grid of the main rectifier valve. "Heenan-Dynamatic" couplings may be supplied either as air- or liquid-cooled units, water usually being employed in the latter case. As a result, larger powers can be accommodated, and a very large speed range is available. The complete range of air- and liquid-cooled couplings covers powers between 1 and 1000 hp. A cross-section through a liquid-cooled coupling, showing its basic constructional features, is given in Fig. 10.

Another example of this type of drive is the "Ajusto-Spede" (Fig. 11), manufactured in the U.S.A. by the Louis Allis Co. The drive motor and air-cooled clutch are built into a single unit which also incorporates a second eddy-current device for use as a brake. Drives of this type are available from $\frac{3}{4}$ up to 75 hp.

A somewhat similar type of drive, with air or water cooling, is produced in the U.S.A. by the Westinghouse Electric Corporation, and in France by Elco (the air-cooled "Elcotron").

Methods of Changing the Synchronous Speed of Induction Motors

(a) Pole-Changing Motors

A truly variable-speed induction motor is a motor in which the synchronous speed is variable. The synchronous speed expressed as a linear velocity is given by twice the pole pitch multiplied by the supply frequency. Pole pitch and frequency are therefore the only quantities which can be used to vary ω_s. The variation of each of these two quantities gives rise to the classes of machine shown as (*a*) (*b*), and (*d*) (*e*) respectively in Fig. 1.

Until recently, the only method of varying pole pitch in an induction motor was to employ a pole-changing winding. Such a machine has a stator winding arranged in such a way that, by means of switches, the stator coils can be re-arranged so as to change the number of poles in the machine. For example, a machine may be wound with two completely independent windings, one producing a six-pole rotating field and the other an eight-pole

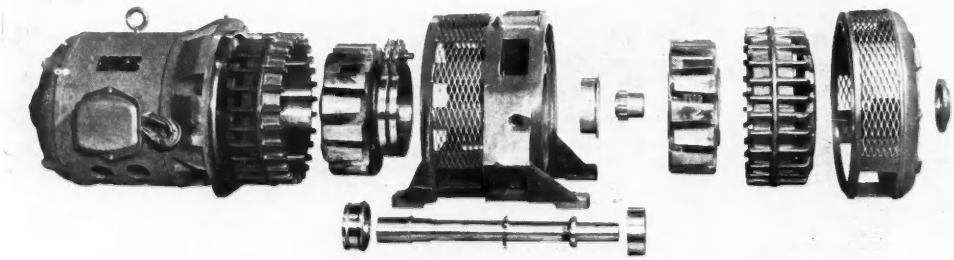


Fig. 11. **Exploded view of the "Ajusto-Spede" drive, using an eddy-current clutch.** (*Courtesy of The Louis Allis Co.*)

rotating field. On a 50-cps supply, such windings give synchronous speeds of 1000 and 750 rpm respectively, and the rotor would normally be a squirrel-cage, so that its operation is unaffected by pole numbers. Such machines are uneconomical insofar as the stator slots must be large enough to accommodate two sets of coils, only one of which is being used, and the resulting machine must therefore have a lower power/weight ratio than either a standard six-pole or eight-pole machine.

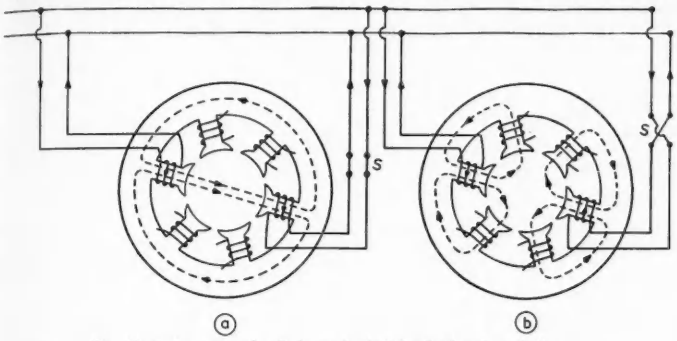
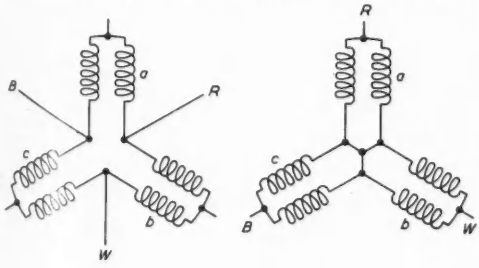


Fig. 12. Arrangement of coils for a simple 2:1 pole-changing winding.

The most common arrangement for a pole-changing winding, however, uses the whole of the stator winding connected in one or other of two ways, as shown diagrammatically in Fig. 12, in which for the sake of clarity only one phase is shown connected. Operation of the change-over switch *S* converts the stator from a two-pole winding (Fig. 12a) to a four-pole winding (Fig. 12b). Clearly, other 2:1 pole-changing windings can be designed in this way.

Although Fig. 12 shows a parallel connection of stator coils, series connection is also practicable, giving four possible combinations. Other arrangements are feasible, depending on whether the winding is star- or delta-connected. Connections can be chosen to give constant horse power, constant torque, or even a more rapidly falling output-speed characteristic. For example, a low-speed, series, delta-connected system changing to a high-speed, parallel, star-connected system gives approximately constant torque. This system is illustrated in Fig. 13. Similarly, with the coils (*a*), (*b*), and (*c*) in Fig. 13, it is possible to produce a high-speed, series delta-connected system or alternatively a low-speed, parallel, star-connected system. In this case, the arrangement is virtually a constant-power system.

Fig. 12 shows that the flux is redistributed in the yoke of the machine as a result of the pole change, and, in the design of pole-changing machines, the depth of iron behind the stator slots must be chosen to limit the maximum flux density in any condition to a reasonable value. The result is that the design of a pole-changing motor involves the sacrifice of operating characteristics at one speed or the other, and often a compromise is adopted. sacrificing a little at both speeds. The efficiency and power factor at the lower speed will generally (as with all a.c. machines) be lower than those associated with the larger pole pitch. During the past few years important development work has resulted in a 3:1 pole-changing machine which makes economical use of winding space[2]. This type of winding increases the range and scope of pole-changing windings considerably.



(a) LOW SPEED (b) HIGH SPEED

Fig. 13. Pole-changing winding for constant torque.

Whilst the 2:1 or 3:1 change can be effected fairly economically, machines having more than two speeds as the result of purely pole-changing windings are not so common, as they introduce problems in winding space. Additional speeds are obtainable if two pole-changing motors are run as a set, coupled both electrically and mechanically ; in fact, a number of speeds is obtainable without pole changing at all. It can be argued that this system therefore falls into class (*e*) in Fig. 1, and not class (*a*). Such a system is known as cascading and is illustrated in Fig. 14, in which motor M_1 is a slip-ring motor supplied from the mains, and motor M_2 is supplied from the slip-rings of motor M_1, the two motors being approximately of the same size.

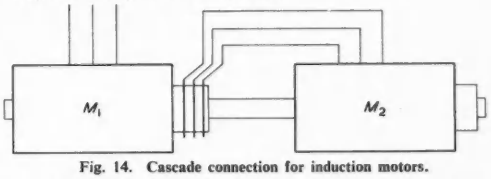


Fig. 14. Cascade connection for induction motors.

At standstill, the effective resistance of motor M_2 is small, and the machine includes only a low impedance in the rotor circuit of motor M_1, allowing the latter to develop torque. As the set accelerates, the slip of M_1 decreases, the frequency supplied to M_2 decreases, and the coupled rotors first reach the vicinity of the synchronous speed of M_2. If the rotors are travelling at the synchronous speed of M_2, the latter appears as a very high impedance across the slip-rings of M_1 and prevents rotor current from flowing in M_1. It is as *if*, in fact, the rotor circuits of M_1 were opened, so that neither machine can produce torque. The set must therefore run somewhat more slowly than this speed, and it can be shown that the motors share the load almost equally.

If motor M_1 has two poles and M_2 has four, three different speeds with a frequency of 50 cps can be obtained, i.e., 3000 rpm, if motor M_1 is run alone with the stator of M_2 short-circuited ; 1500 rpm, if motor M_2 is run alone by switching the mains supply to the stator of M_2 ; and 1000 rpm, if the motors are run in cascade. If both motors carry pole-changing windings, the number of possible speeds can be considerably increased by a suitable choice of pole numbers.

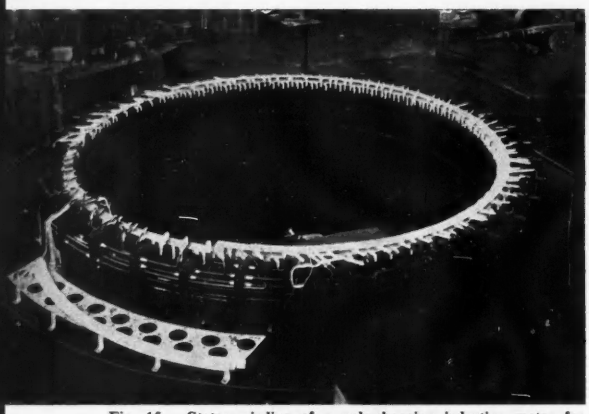


Fig. 15. **Stator winding of a pole-changing induction motor for 2500/2500 kW, 5000 V, 250/333 rpm.**
(Courtesy of AEG)

Pole-changing motors of 2, 3, and 4 speeds are manufactured in a wide range of sizes, including very large models, such as that illustrated in Fig. 15.

(b) Continuously Variable Pole-Pitch Motors

At the same time as the 3:1 pole-changing motor was being developed, a new principle was discovered, enabling continuous variation in pole pitch to be effected[3]. The new principle may be stated simply as follows :—If the rotor of an induction motor is constrained to move so that its surface velocity makes an angle θ with the direction of motion of the stator field, the rotor will be accelerated towards the speed $v_s/\cos\theta$, where v_s is the linear field velocity. In terms of the disc machine shown in Fig. 16, the principle may be exploited by rotating the stator block from the position shown in Fig. 16a, to that shown in Fig. 16b to increase the speed. Fig. 17 illustrates how the increase in θ produces effective increase in pole pitch. A rotor moving along the direction AB is under the influence of pole pitch PQ. If the rotor is constrained to move parallel to CD, it experiences a pole pitch PR, where $PR = PQ/\cos\theta$.

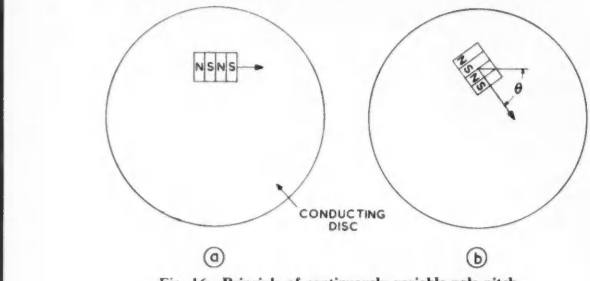


Fig. 16. **Principle of continuously variable pole pitch.**

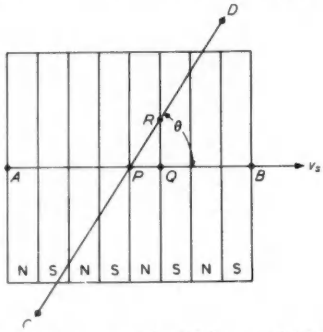


Fig. 17. **Increase of pole pitch by an angled field.**

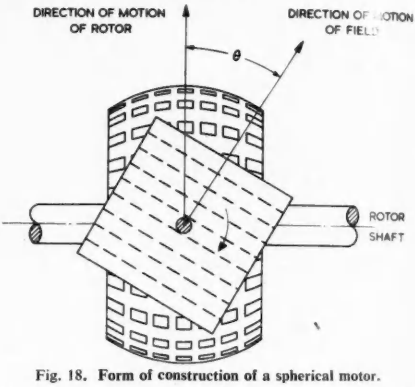


Fig. 18. **Form of construction of a spherical motor.**

To make better use of the materials in this type of machine, it has been found preferable to construct the rotor as part of a sphere [4,5], so that the stator blocks can be suitably orientated relatively to the rotor whilst maintaining constant air-gap. The form of construction is illustrated in Fig. 18, and a prototype machine in Fig. 19. The rotors of spherical motors must be capable of conduction in all directions in sensibly the same manner as a conducting sheet, this being achieved in practice by using peripheral conducting rings in addition to the conventional cage bars. The mesh of rotor conductors can, in fact, be cast in the same manner as the rotors of conventional cylindrical machines, and experimental work has so far demonstrated that the power/weight ratio of such a motor may be higher than that of any other type of continuously variable-speed machine. Although, in theory, any desired speed range can be achieved, and in practice 5·5:1 has been realized, machines with a designed range of more than 3:1 are not at present envisaged, although pole-changing windings may possibly be incorporated to extend this range.

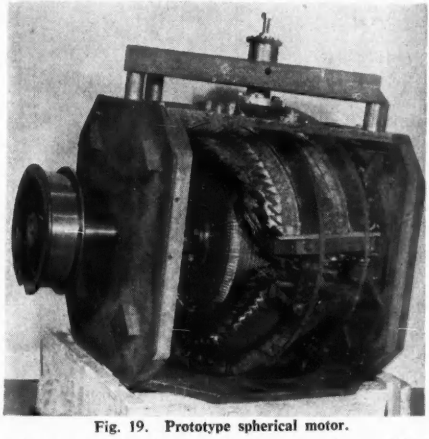


Fig. 19. **Prototype spherical motor.**

Spherical motors are virtually constant-power

machines, although present development work is being carried out with a view to the production of a more nearly constant-torque version. For reasonably high efficiency the spherical motor is essentially multipolar, operating up to a maximum speed of 1000 rpm. The advantages of the spherical motor are that a cast rotor, requiring no brushes or rubbing contacts, is used ; there is virtually constant efficiency over the speed range ; it is inherently flameproof and robust ; and it has a high power/weight ratio.

The cost of production is still under investigation, but it appears that it may be lower than that of most other continuously variable-speed a.c. motors, and it seems that this new motor must now take its place in the table in Fig. 1 in a hitherto unoccupied group (*b*). The first commercially produced motor of this type is illustrated in Fig. 20.

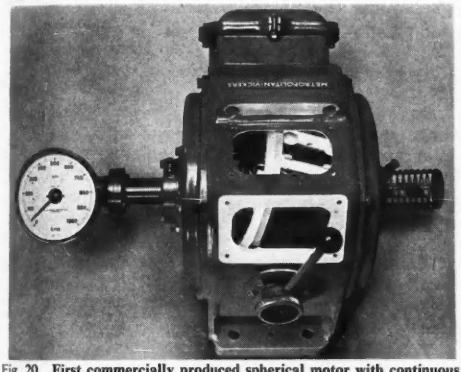


Fig. 20. **First commercially produced spherical motor with continuous speed variation over a 3:1 range.**
(*Courtesy of Metropolitan-Vickers Electrical Co. Ltd.*)

A second type of continuously variable pole-pitch motor is also under investigation at the present time.[5] This machine also exploits the principle of the angled field, but variation of θ is effected by means of a phase-shifting regulator. This obviates the necessity for the spherical shape, but introduces extra equipment in the form of the phase-shifter. This motor is still in a very early stage of development, but it is possible that it may provide continuously variable speed in the range between 1000 and 3000 rpm on a 50-cps mains supply. Incidentally, an interesting analogy to this type of motor is that operated by supplying movable brushes directly or by supplying fixed brushes via a phase-shifting regulator.

All variable pole-pitch machines can exploit fully the principle of regenerative braking already discussed, and any reduction in required speed results in a period of deceleration in which the excess kinetic energy of both rotor and load is reconverted into electrical energy and returned to the supply.

(c) Squirrel-Cage Motors with Variable Supply Frequency

There are several methods of changing electrical a.c. power from one frequency to another. If a fixed frequency change is required, it may be effected, for example, by a pair of mercury-arc converters working back-to-back to give a 3:1 step-down ; such an arrangement is used in traction systems employing single-phase, series a.c. motors. An increase in frequency may be obtained by utilizing the non-linear properties of saturated iron. Saturated transformers can be connected in such a way as to eliminate the fundamental frequency and to deliver, as a triple-frequency output, the third harmonic voltage. Such methods, however, are not generally used for driving squirrel-cage induction motors, as they are limited to fixed speeds, although in special circumstances they can be useful. For example, the triple-frequency method has been used to operate a 3-phase induction motor at over 8000 rpm from a 50-cps supply for an application where the use of commutators was forbidden.

Systems which are capable of producing a continuously variable supply frequency over a considerable range fall into two classes, i.e., (a) the commutator class, and (b) the induction frequency-changer class. In all cases where a commutator is used it is invariably the practice to fit the frequency changer to the motor to be supplied, and as such the machine falls under group (*d*) in Fig. 1. This section is not concerned with commutator motors, and therefore only the induction type of frequency changer is now considered.

The induction frequency changer is nothing more than an ordinary wound-rotor, slip-ring induction motor which can be driven mechanically by a variable-speed unit. The stator of the induction machine is connected to the main supply, and the slip-rings are connected to the squirrel-cage motor whose speed is to be varied, the system being illustrated in Fig. 21. The variable-speed unit need not be an electric motor at all. It is clear that such a system does not solve the problems of variable speed, but merely shifts the responsibility onto another motor, i.e., the variable-speed unit. The advantages of this system, therefore, lie primarily in that the final drive motor is a brushless machine with all its attendant advantages over commutator machines, and, although a commutator motor may be used to drive the frequency changer, it may be situated, as distinct from the final drive motor, in a locality where commutators are not prohibited. A further advantage is that a number of motors can be driven from the one frequency changer, so that the speed of all the motors can be controlled simultaneously. If the variable-speed unit used to drive the frequency changer is an a.c. commutator motor, some economy in equipment can be effected by designing the set so that the stator field of this motor and that of the induction frequency changer are one and the same.

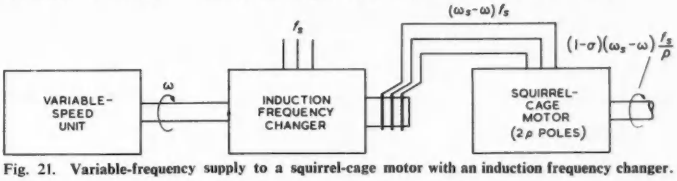


Fig. 21. **Variable-frequency supply to a squirrel-cage motor with an induction frequency changer.**

Fig. 21 shows how speed regulation occurs in this type of drive as the result of two distinct processes. If the frequency $(\omega_s - \omega)f_s$ supplied to the squirrel-cage motor is maintained constant as the machine is loaded, speed regulation is given simply by the slip σ of the squirrel-cage motor ; the greater the load, the greater is the slip. However, the greater the slip, the lower will be the equivalent impedance of the motor and the greater the current taken from the slip-rings of the frequency changer. Suppose that the speed of the rotor of the frequency changer is ω

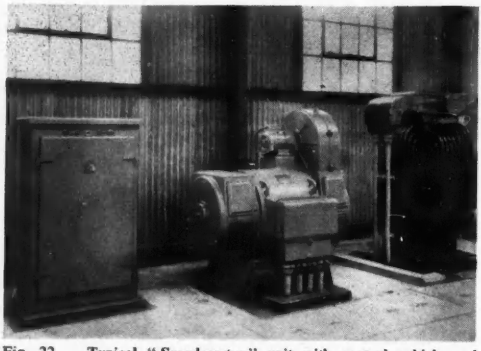


Fig. 22. Typical "Speedmaster" unit with control cubicle and induction regulator.
(Courtesy of Laurence, Scott & Electromotors Ltd.)

and that it has p pairs of poles, so that $\omega_s = f_s/p$ and $\omega_s > \omega$. As more and more current is taken from the slip-rings the frequency changer tends more and more towards becoming a normal induction motor with a short-circuited rotor which attempts to run at a speed of ω_s. Thus, the frequency changer tends to speed up towards ω_s, delivering a lower frequency to the squirrel-cage motor and lowering in turn the synchronous speed. If a number of motors is being driven from one frequency changer, excessive load on one motor will therefore tend to lower the speed of all the others to a lesser degree.

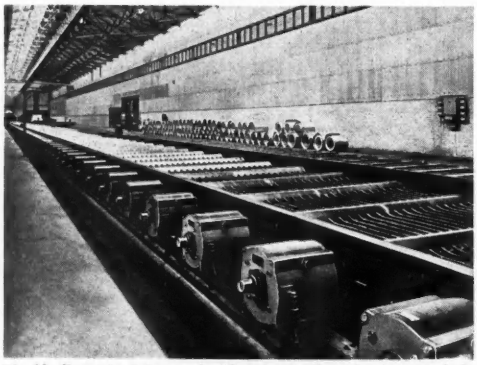


Fig. 23. Example of the use of a "Speedmaster" unit for the control of a large number of floating-type slave motors on a run-out table in an aluminium strip mill.
(Courtesy of Laurence, Scott & Electromotors Ltd.)

To some extent, the criterion relating efficiency with pole pitch is eased in this type of drive. For a given speed, the pole pitch and frequency are inversely proportional to one another, whereas the rotor time-constant is proportional to the square of the pole pitch. Thus, if the criterion τf be taken as a measure of performance, then the bigger the pole pitch, the better will be the performance, i.e., τf is proportional to p.

Although cascaded induction motors were described in the section on pole-changing windings, they really belong to the class of motors at present under discussion, since the motor M_1 in Fig. 14 acts as a frequency changer for the motor M_2 and at the same time provides some of the mechanical power output. The system shown in Fig. 21, when arranged with a combined motor and frequency-changing machine, is, in effect, an extension of the cascade system to continuously variable speed.

One of the best-known commercial examples of an induction frequency changer driving a squirrel-cage motor is the "Speedmaster" produced by Laurence, Scott & Electromotors Ltd. The variable-speed motor in this set is effectively an "N-S" type of commutator motor (to be described later), also manufactured by this firm. The system is made more compact, as shown in Fig. 22, by combining the drive motor and frequency changer into a single machine with a common stator winding. The rotor carries a commutator at one end and slip-rings at the other. This machine is therefore a self-propelled frequency changer which can be used to drive any number of "slave" brushless induction motors. Fig. 23 shows an example of the use of a "Speedmaster" unit for control of a large number of slave motors operating over a frequency range of 8 to 37 cps. If exact synchronism is required for all the slave motors, synchronous motors may be used in place of the squirrel-cage motors.

An interesting application in which a frequency changer is almost indispensable is provided by an A.E.G. motor capable of speed variations between 6000 and 60,000 rpm, this top-speed requirement demanding a solid robust rotor. The motor is driven by a high-frequency generator capable of delivering a maximum frequency of 1000 cps, and the generator is driven by a Ward-Leonard set which, in turn, is driven by a 3-phase, 50-cps induction motor. The requirements of this project thus result in the use of no less than six machines.

Polyphase Commutator Systems

Once the properties of a commutator are fully understood, the action of a polyphase commutator motor can be explained fairly simply in terms of induction-motor theory. Although ring windings are very primitive and are now used in hardly anything but demonstration equipment, diagrams of commutator motors are perhaps easiest to understand in terms of ring windings. The diagrams in Fig. 24 represent the ring-wound rotors of two machines. In Fig. 24a, the winding is tapped at many points and is connected to commutator segments, three brushes, spaced 120 deg. apart, making contact with the commutator. In Fig. 24b, the winding is tapped at only three points which are connected to three slip-rings. Fig. 24b thus represents a delta-connected rotor of a normal slip-ring induction motor.

When each rotor is at rest the two types are indistinguishable, each producing a rotating field of angular speed $\omega_s = f_s/p$. If the rotor shown in Fig. 24a is now

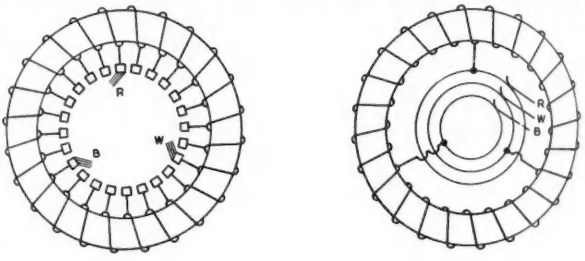


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Fig. 24. Commutator and non-commutator types of rotors.

rotated at a speed ω, the commutator ensures that the 3-phase supply is always led in at the same three points relative to the frame of the machine, i.e., relative to the brushes. The speed of the field in space is therefore unaltered, but the rate at which the winding cuts its own field is changed. As the rotor is accelerated from rest, the relative velocity between field and winding is reduced, being, in fact, $\omega_s - \omega$. The self-induced e.m.f. is therefore proportionately reduced, and the inductive reactance per phase is reduced from a value X_s at standstill to σX_s at a slip σ. At $\omega = \omega_s$ the input impedance of the rotor consists simply of the winding resistance. For $\omega > \omega_s$ the winding cuts the field it produces in the opposite sense, giving rise to an oppositely phased induced e.m.f., and the input inductive reactance is negative, i.e., the rotor displays the properties of a condenser and resistance in series.

In the rotor shown in Fig. 24b, the 3-phase supply is effectively connected permanently to the winding. If the winding is rotated at a speed ω, the field in space rotates at $\omega_s + \omega$ if the rotation is in the same direction as the field, or $\omega_s - \omega$ if in the opposite direction.

The operation of each system when the windings are cut by externally produced fields can now be deduced. Since the rotor in Fig. 24a always produces a field rotating in space at a speed ω_s, irrespective of the rotor speed, it follows that, if a field of speed ω_s is generated by some external stator winding, the frequency appearing at the brushes will be f_s and independent of the rotor speed, even though the frequency induced in the winding itself is $(\omega_s \pm \omega)p$, i.e., σf_s. In the case of Fig. 24b, the frequency σf_s induced in the winding is simply transmitted directly to the brushes. The properties of these two types of winding are summarized in Table I.

TABLE I: PROPERTIES OF COMMUTATOR AND NON-COMMUTATOR TYPES OF ROTORS

	Winding as in Fig. 24a	Winding as in Fig. 24b
Speed of field in space produced by a frequency f_s applied to the brushes	ω_s	$\omega_s \pm \omega$
Rate at which the winding cuts its own field	$\omega_s \pm \omega$	ω_s
Reactance of the winding as measured at the brushes	σX_s	X_s
Frequency induced in the winding by an external field of speed ω_s	σf_s	σf_s
Frequency appearing at the brushes due to a field of speed ω_s	f_s	σf_s

It is a property of commutators that the frequency which appears at the brushes is a measure only of the relative velocity between the field and the brushes and is independent of the velocity of the rotor winding.

In a slip-ring induction motor, the leads from the slip-rings simply carry away power to the external resistance, and there is no reason why eq. (1) should not read

$$\sigma = \frac{\text{rotor power extracted}}{\text{rotor input}}$$

If the extracted power can be fed back to the supply, efficient speed control can be achieved. The reason why direct connection between slip-rings and main supply is not possible is that rotor current is at slip frequency. One of the earliest schemes for speed control by means of a commutator was the Leblanc exciter, in which the rotor of an auxiliary machine was coupled to the induction-motor shaft. The rotor of the auxiliary machine was wound according to Fig. 24a and the brushes were connected to the slip-rings of the induction motor. The rotor of the auxiliary machine was also tapped at three points and connected to slip-rings, as in Fig. 24b, the slip-rings being connected to the mains through a variable-tapping transformer. The auxiliary machine required no stator winding, its function being merely to convert the supply frequency supplied to the slip-rings of the motor to slip frequency at the brushes, and this it was always able to do, since the two machines were mechanically coupled.

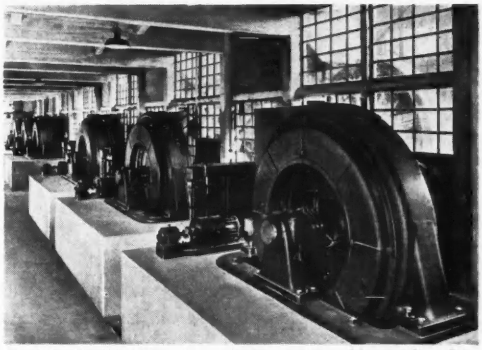

Fig. 25. Six 620-kW, 144-rpm, 3-phase motors with statorless phase advancers.
(*Courtesy of Brown, Boveri & Company Ltd.*)

It is of interest here to note that a similar system can be used for the power-factor improvement of an induction motor. The impedance of the winding shown in Fig. 24b as measured across the slip rings is independent of the speed of the winding, since the latter always cuts its own field at synchronous speed. The impedance of the winding in Fig. 24a, however, changes with speed, since the rela-

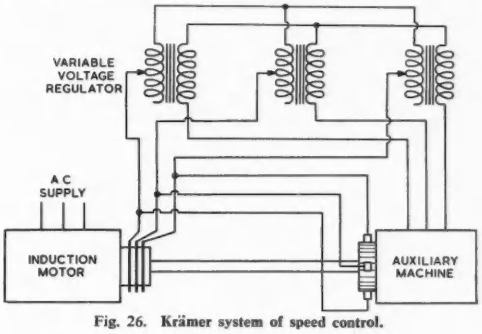

Fig. 26. Krämer system of speed control.

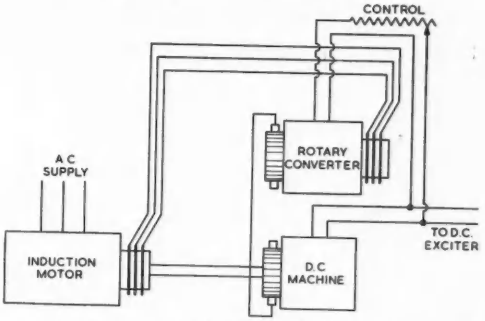

Fig. 27. Krämer system of speed control using rotary converter.

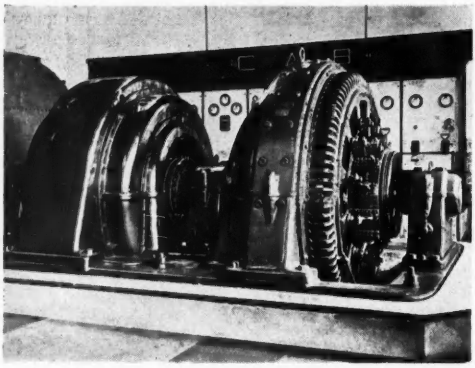

Fig. 28. **1850-kW, 3000-V, 50-cps, 600-rpm rolling-mill motor with a d.c. auxiliary motor, connected in Krämer cascade.**
(*Courtesy of Brown, Boveri & Company Ltd.*)

tive velocity between field and winding is $\sigma\omega_s$ (Table I).

At synchronous speed the winding is purely resistive as measured at the brushes. For speeds in excess of synchronism the effective reactance becomes negative. This principle is applied to the phase advancer, as follows: The slip-rings of an induction motor are connected to the brushes of an auxiliary machine carrying a rotor winding of the type shown in Fig. 24a. The synchronous speed of the field in space in the auxiliary machine is therefore the slip speed of the induction motor. It is only necessary to drive the auxiliary motor a little faster than this speed in the same direction, to make it act like a large condenser in series with the rotor of the induction motor and to improve the power factor of the latter.

The stator of the auxiliary machine carries no winding. In fact, the rotor can be designed in such a manner as to complete the magnetic circuit without a stator at all. The relative size of main drive motor and phase advancer is illustrated by the example in Fig. 25, which shows six Brown Boveri 3-phase motors with statorless phase advancers.

All commutator speed-control systems depend in principle on the modified form of eq. (1), i.e., that the rotor power is the net result of power radiated across the air-gap by direct induction-motor action and of the power conveyed to or from the rotor by electrical contact through brushes. Clearly, such machines can run above, as well as below, synchronous speed, since, when power is being added to the rotor by the conduction device, the slip becomes negative, and the final form of eq. (1) is therefore

$$\sigma = \frac{\text{rotor power extracted or injected}}{\text{rotor input}}$$

Many forms of speed-control device are based on this principle.

The Krämer System

Two forms of the Krämer system are illustrated in Figs. 26 and 27. In Fig. 26, the stator of the auxiliary machine is fed from the slip-rings of the main motor, the speed of the field of the auxiliary being therefore $\sigma\omega_s$. The frequency at the brushes is thus σf_s, which can be fed back to the slip-rings of the main motor. The voltage across the brushes of the auxiliary is varied by means of the tapped transformer in the stator circuit. This system effectively extracts power from the rotor circuits of the main motor and converts it to useful drive, the auxiliary motor sharing in the mechanical load.

The system shown in Fig. 27 makes the action perhaps a little more obvious in that the rotor energy extracted is converted to direct current by means of a rotary converter and then used to assist in driving the load by feeding it to a d.c. motor on the same shaft. Speed regulation is effected by means of the d.c. motor field rheostat. When the field current is altered, the d.c. voltages of both d.c. motor and rotary converter are changed, and hence the a.c. voltage of the latter, since a.c. and d.c. voltages have a fixed ratio in a rotary converter. The arrangement is suitable for a wide speed range.

Fig. 28 shows a Krämer set with rotary converter, manufactured in Switzerland by Brown-Boveri & Co. Ltd., for use in a rolling mill.

The Scherbius System

The Scherbius system is illustrated in Fig. 29, in which the auxiliary commutator machine in this case is separately driven by an auxiliary induction motor. This is advantageous in that the commutating machine may be designed to run at a particular speed which is more or less independent of the main motor speed.

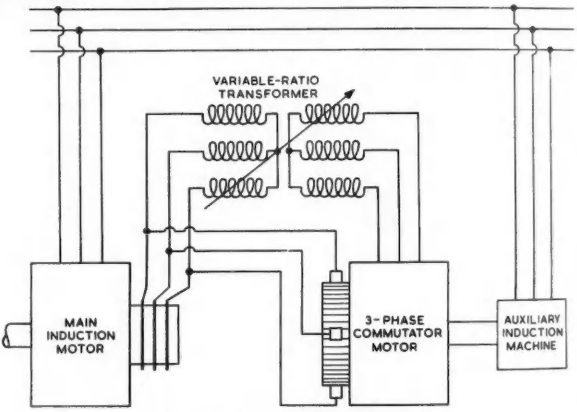

Fig. 29. **Scherbius system of speed control.**

The action of the system is similar to that of the Krämer system shown in Fig. 26, except that the power extracted from the rotor can be fed back as electrical power to the mains by means of the auxiliary induction machine, which acts as a generator if the speed of the main motor is less than synchronism.

The capacity of the auxiliary machine is dependent on the desired speed range, since it is the mechanism of feedback of surplus energy. The greater the speed range the greater will be the required capacity of auxiliary machines. The speed range can be doubled by running the main motor both above and below synchronism, but the arrangement shown in Fig. 29 will not provide synchronous running, since the slip e.m.f. then becomes zero. Separate excitation is therefore required in this region, and this is provided by means of a Leblanc exciter driven from the main motor shaft and connected to the commutator machine field.

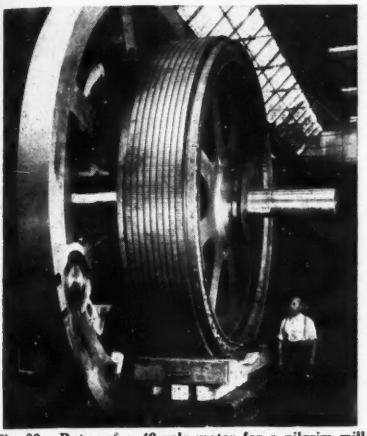

Fig. 30. **Rotor of a 48-pole motor for a pilgrim mill.** (*Courtesy of Brown, Boveri & Company Ltd.*)

Power-factor correction is possible by altering the phase of the e.m.f. applied to the main-motor slip-rings. This may be achieved either at the cost of auxiliary windings on the regulating transformers, which may be connected in series with a different phase, or by insertion of a resistance into the control circuit at a cost of lower efficiency. A power factor of about unity may be obtained over most of the speed range, except in the vicinity of synchronous speed.

Motors for rolling mills are almost invariably slow-speed multi-pole motors, which therefore tend to be of large diameter. Fig. 30 shows the rotor of the main induction motor of a Scherbius set, made in Switzerland by Brown, Boveri & Co. Ltd., with 48 poles and a synchronous speed of 125 rpm. Similar machines may have as many as 108 poles.

Polyphase Commutator Motors

All the systems so far described have involved the supply of slip-frequency current to the slip-rings of an induction motor, and as such are included under group (*e*) in Fig. 1. The rotor shown in Fig. 24a, however, indicates that an alternative approach to the energy injection-extraction principle is possible, since the rotating field of an induction motor inducing e.m.f. into the rotor winding will always result in the stator supply frequency appearing at the brushes, and therefore rotor power injection or extraction is possible directly by a static voltage regulator. Such machines are included in group (*d*) in Fig. 1, the commutator being on the drive motor itself. The basic circuit of a shunt commutator motor is shown in Fig. 31.

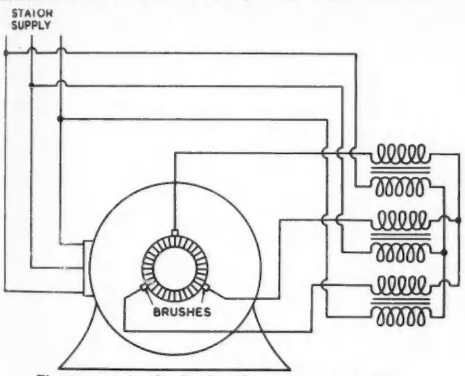

Fig. 31. **Basic circuit of a shunt commutator motor.**

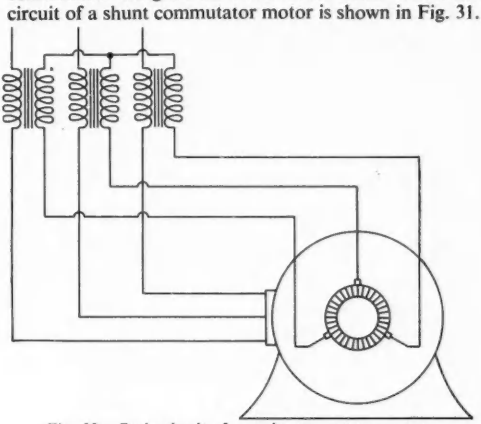

Fig. 32. **Basic circuit of a series commutator motor.**

Rotation of the set of brushes relative to the frame of the machine alters the phase of the brush e.m.f. relative to the respective phases of the supply. This effect is exploited in the early brush-shifting type of commutator

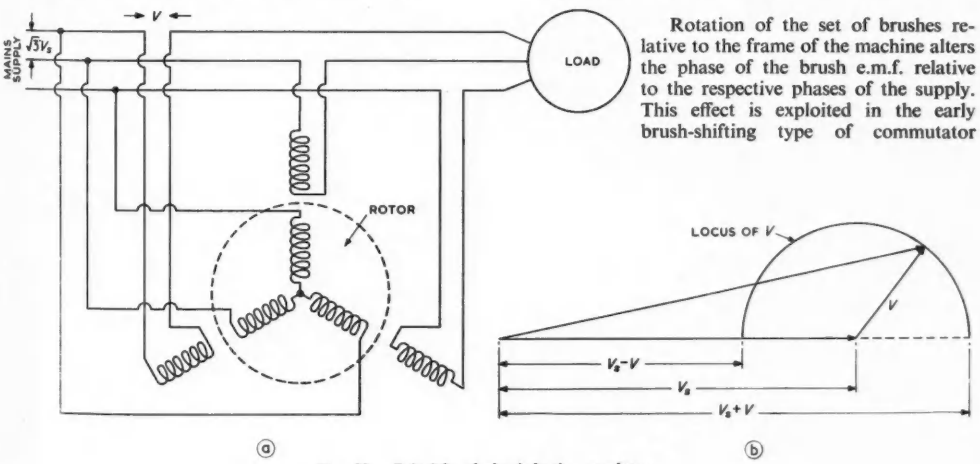

Fig. 33. **Principle of the induction regulator.**

motor, in which rotation of the brushes is used to change the amount of power extracted from or injected into the rotor circuit via the commutator.

A similar effect can be achieved if the brushes are maintained in a fixed position, but supplied by a phase-shifting transformer, in place of the conventional transformer shown in Fig. 31. A phase-shifting transformer is basically an induction motor with a locked rotor, the position of the rotor, however, being variable relative to the stator over a range of something less than 360 deg. The supply from the rotor is taken out by flexible leads, and the rotor may be controlled by a worm drive to prevent its rotation as the result of normal induction motor torque.

A motor with series characteristics may be produced by connecting the primary of the transformer in series with the stator winding, as shown in Fig. 32.

In more modern machines an induction voltage regulator is used to vary the magnitude of the voltage supplied to fixed brushes. The principle of the induction regulator is shown in Fig. 33a, where the secondary of a phase-shifting transformer is connected in series with the supply to the load (in the case of commutator motors, the rotor brushes). The vector diagram in Fig. 33b shows that the voltage supplied to the load can be varied between $V_s - V$ and $V_s + V$, but that at intermediate settings the phase of the applied voltage will also be affected to an extent depending on the relative values of V_s and V.

If nothing more than a simple induction regulator were used, the commutator motor would tend to have a low power factor, and commutation would be poor, resulting in sparking, with associated brush wear and burning of the commutator. Commutation in a.c. machines is generally a much greater problem than in d.c. machines. In the latter, only a current-reversing e.m.f. is necessary to ensure good commutation, and this can be supplied by using interpoles. In the a.c. machine there is the additional complication of transformer e.m.f. induced in the rotor coils, which, at the instant of commutation, are short-circuited by the brush. Interpoles are ineffective in a.c. machines because the phase of the e.m.f. they can produce is in quadrature with the e.m.f. which it is desired to neutralize, and therefore the two can never cancel. A further point to remember is that, for a given effective rotor current, the a.c. commutator is required at worst to reverse $\sqrt{2}$ times as much current as the d.c. commutator, because of the relationship between peak and r.m.s. values.

(a) The N-S Motor

In this modern commutator motor, manufactured in the U.K. by Laurence, Scott & Electromotors Ltd., power factor is improved by means of a compensating quadrature winding which injects a voltage into the rotor circuit, leading the voltage at the commutator by 90 deg. The source of this voltage is either an additional winding on the stator of the motor or a separate transformer fed from the supply.

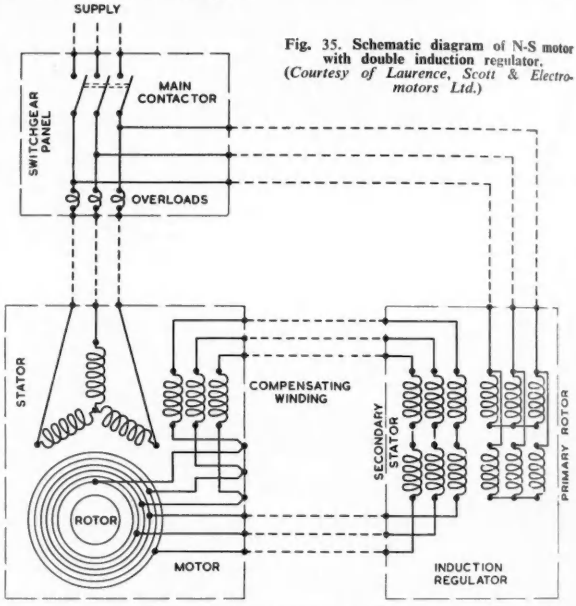

Fig. 35. Schematic diagram of N-S motor with double induction regulator. *(Courtesy of Laurence, Scott & Electromotors Ltd.)*

Commutation is improved by the use of a further auxiliary winding in the rotor. The disposition of this winding with respect to the main winding is shown in Fig. 34. The auxiliary winding is so arranged that the voltage induced in it by the main field is equal to that induced in the main winding connected to the same commutator segments, so that no equalizing currents flow. The auxiliary winding is effectively a set of built-in transformers which enable the energy which would otherwise produce a spark to be transferred to another part of the main winding. The auxiliary winding also tends to reduce the transformer-induced voltage between neighbouring commutator segments.

Since rotation of the brushes produces effective phase shift between rotor-induced e.m.f. and externally applied e.m.f., there must be a correct position for the simple arithmetical addition or subtraction of these voltages. Furthermore, when the external voltage is zero, the rotor is effectively short-circuited, and the brush position has no

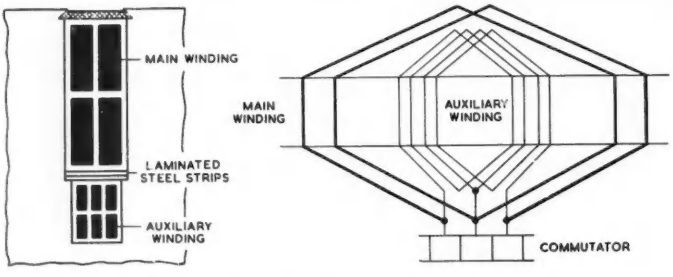

Fig. 34. Arrangement of commutating winding in a N-S motor. *(Courtesy of Laurence, Scott & Electromotors Ltd.)*

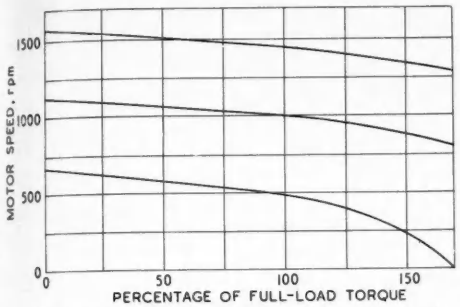

Fig. 36. **Typical speed-torque curves for a N-S motor at various regulator settings.**
(Courtesy of Laurence, Scott & Electromotors Ltd.)

effect. To produce speeds in excess of synchronism requires a voltage of opposite polarity to that required for sub-synchronous running, and this 180-deg. phase shift must be provided for externally, if the necessity for rotating the brushes through 180 deg. as the machine passes through synchronous speed is to be avoided. In the N-S motor this is achieved by means of a double induction regulator, the complete circuit of the motor being shown in Fig. 35. This type of motor has been supplied for speed ranges up to 50:1 and normally has constant torque with shunt characteristics, although a series arrangement can be designed. Power output can be as high as 1000 hp for a 2:1 speed range. Speed-torque curves over a 3:1 speed range are shown in Fig. 36.

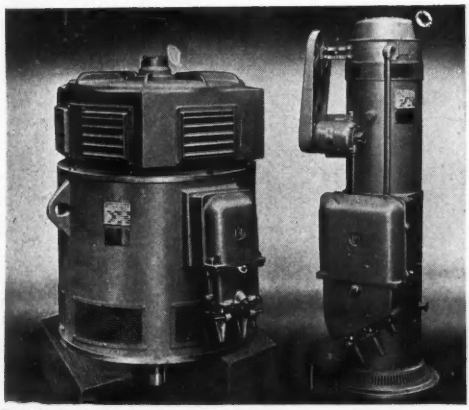

Fig. 37. **Vertical-spindle, drip-proof N-S motor with a pilot-motor-operated air-cooled induction regulator.**
(Courtesy of Laurence, Scott & Electromotors Ltd.)

The induction regulator is usually of the air-cooled type for small and medium-size motors, or of the oil-immersed type for larger motors or for use where the atmospheric conditions are unsuitable for forced-air-cooled regulators and above the size for which totally enclosed air-cooled regulators may be used. These regulators may be arranged for handwheel or pilot-motor operation, or for direct drive from any suitable type of automatic regulator. A vertical-spindle, drip-proof N-S motor with a pilot-motor-operated air-cooled induction regulator is shown in Fig. 37.

(b) The Schrage Motor

The Schrage motor is an example of the modern type of brush-shifting polyphase commutator motor which also aims at combined speed and power-factor control. Most electrical machines will operate quite well if their stator and rotor members are interchanged, although there is generally a preferred arrangement. For example, a d.c. machine with a rotating field system would require both slip-rings and a commutator, as well as rotatable brushes, but it would nevertheless operate quite well. In the case of a squirrel-cage induction motor, the obvious choice is to feed in the supply to the stator, leaving the self-contained rotor to move without requiring any brushes. In a wound-rotor induction motor with slip-rings which are in continuous operation, there is little to choose ; in the case of the Schrage motor it is certainly more convenient to supply what would normally be the stator or primary winding of the motor through slip-rings, and this winding is housed in the rotor slots. The same slots contain a second winding, which is of the d.c. lap type, connected to a commutator. The rotor of the Schrage motor thus comprises both a winding of the type shown in Fig. 24a and one of the type shown in Fig. 24b. Since each end of each phase of the stator is connected to a brush, making six in all, they are generally referred to as " half-brushes ". Nos. 1, 3, and 5 (Fig. 38) are connected

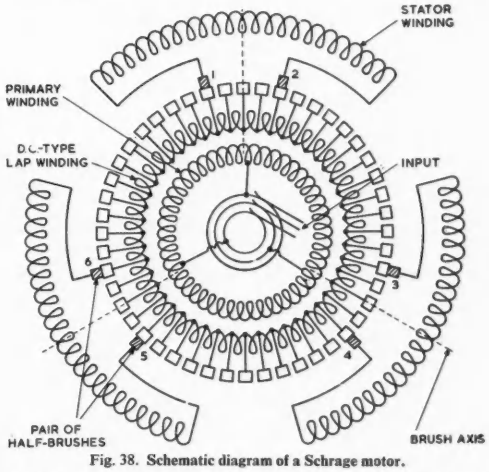

Fig. 38. **Schematic diagram of a Schrage motor.**

to a rocker, whilst Nos. 2, 4, and 6 are connected to a second rocker, not in the same plane. The rockers are arranged to rotate so as to move the half-brushes apart or together in pairs, keeping the axes of the pairs of half-brushes in the positions shown by the dotted lines. The half-brushes can be moved together, until any pair lie on the same segment (Fig. 39b) and subsequently crossed over and moved apart, as shown in Fig. 39c.

When the half-brushes are lying in pairs on the same segments, the stator windings are short-circuited through the brushes. The lap winding plays no part in the action

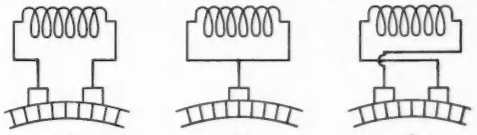

Fig. 39. **Brush positions in a Schrage motor, showing (a) half-brushes in the sub-synchronous position, (b) stator short-circuited, and (c) half-brushes in the hyper-synchronous position.**

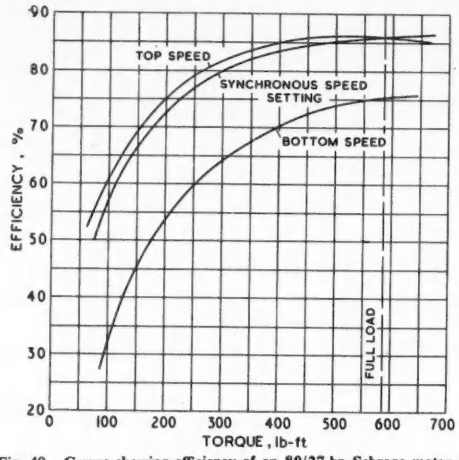

Fig. 40. Curves showing efficiency of an 80/27-hp Schrage motor at various speeds.
(Courtesy of Metropolitan-Vickers Electrical Co. Ltd.)

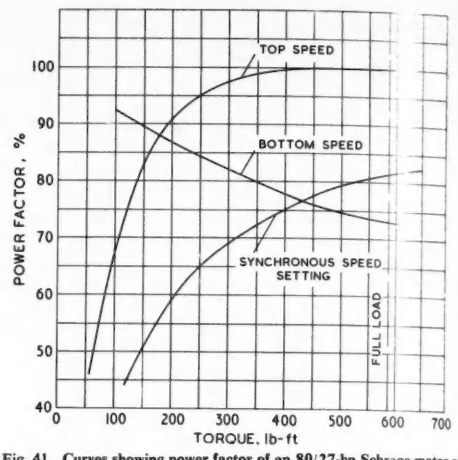

Fig. 41. Curves showing power factor of an 80/27-hp Schrage motor at various speeds.
(Courtesy of Metropolitan-Vickers Electrical Co. Ltd.)

of the motor in this condition and the machine runs as an inverted induction motor, at a small slip when on load.

The primary-lap combination behaves like an ordinary transformer, which, however, is rotated at a speed ω; like an ordinary transformer, the secondary voltage can be tapped by opening out the pairs of half-brushes, and the greater the brush spread the greater will be the voltage. Furthermore, because the speed of the field in space is $\omega_s \pm \omega$, being produced by a winding of the type shown in Fig. 24b, and the half-brushes are stationary, the frequency at the brushes is $(\omega_s \pm \omega)p$, i.e., σf_s. The half-brushes can therefore be connected directly to the appropriate stator windings, since these have induced e.m.f. of slip frequency through normal induction-motor action. The phase of the brush e.m.f., relative to the stator-induced e.m.f., depends on the position of the axes of the pairs of half-brushes. Although the power factor of the machine can be varied by moving the brush axes, a different axis is required for each speed setting, and it is usual in practice to fix the position of the axes at some advantageous position (e.g., the position which gives a power factor of unity at peak speed and output), and simply to alter the brush spread by means of the rockers to control the speed.

The action of the rotor may be summarized by saying that the primary-lap combination, together with the six half-brushes, behaves like an extremely versatile transformer in that it has (a) a variable turns ratio, (b) a variable frequency ratio, and (c) a variable phase relationship, primary to secondary.

With the half-brushes in positions such as those shown in Fig. 39a, the motor runs at sub-synchronous speeds, as power is being extracted from the stator and returned to the supply. With the half-brushes in the positions shown in Fig. 39c, power is being supplied to the stator through the brushes, in addition to that already being transferred inductively across the air-gap.

The advantages of the Schrage motor are that it is self-contained and that it can have a power factor of unity, at one setting at least, with reasonably good power factor over most of the range. Like other commutator motors, it has regenerative braking.

There is a limiting factor to the size of Schrage motors. For a given speed range the maximum output per pole is limited by the current density in the brushes. The problem of commutation, as in other a.c. commutator motors, is twofold, i.e., that of the current-reversing e.m.f. and of the transformer e.m.f. The former is current-dependent, and the greater the departure from synchronous speed, the greater will be the current through the brushes. The

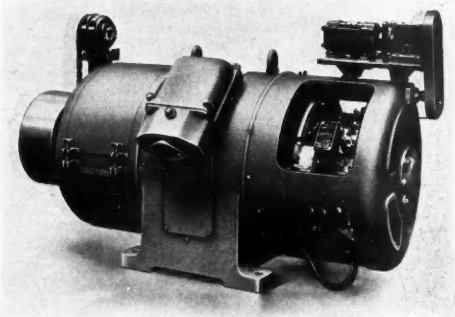

Fig. 42. Schrage motor with forced ventilation, equipped with pilot-motor-operated brushgear.
(Courtesy of Metropolitan-Vickers Electrical Co. Ltd.)

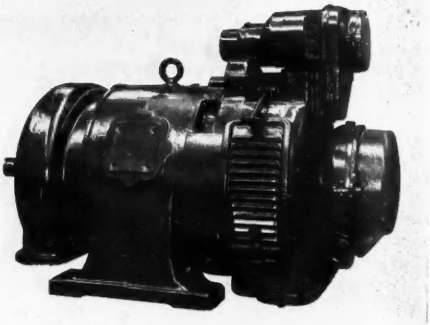

Fig. 43. Schrage motor of drip-proof design, with motor-operated brushgear.
(Courtesy of ASEA)

only possible methods of increasing output, once the current has reached its maximum permissible value, is to increase the number of poles or to increase the number of phases. The latter is usually impractical because of the supply problem. There is a limit to the former, since an increase in the number of poles, without an increase in frame size, results in lower power factor and efficiency, apart from the natural reduction in synchronous speed. Until recently, the maximum output per pair of poles was about 35 hp for a 3:1 speed range with a 50-cps supply; modern practice, however, is to use duplex windings to halve the current at the brushes, and an auxiliary winding similarly disposed to that in the N-S motor to provide connection between the two halves of the duplex winding and to reduce current reversal in a complete half of the winding to current reversal in only a few coils. In this way the maximum power output per pole has been doubled for a given speed range at the cost of the auxiliary winding. Although Schrage motors can have a designed speed range of 10 : 1, they are not normally chosen for more than a 4 : 1 variation. Typical efficiency and power-factor curves are shown in Figs. 40 and 41.

Schrage motors are undoubtedly the commonest a.c. commutator motors. Figs. 42 and 43 illustrate typical arrangements incorporating a small pilot motor to move the brush rockers, this motor being situated, as shown, on top of the main motor. A similar type of equipment is produced by Siemens-Schuckert A.G., by Higgs Motors Ltd., and by many other manufacturers throughout the world. In one design, produced in the U.K. by Reyrolle & Co. Ltd., the controller operated by the brushgear motor is fitted with a preset speed device, which causes the motor to accelerate from standstill to any predetermined speed when the start-button is operated. Thereafter, speed is under the control of "increase" and "decrease" push-buttons.

Disadvantages of Commutator Motors

The foregoing descriptions of commutator motors bring out one point above all others in discussing the advantages and disadvantages of this method of speed control, i.e., the complexity of the equipment, which invariably involves increased cost and low power/weight ratio. The Krämer and Scherbius systems involve more than one machine, plus a quantity of auxiliary equipment. The N-S motor requires additional windings and a separate induction regulator. The Schrage motor contains two rotor windings (or three, if an auxiliary is used) and a complicated brush rocker system, in addition to slip-rings and brushes.

All commutator motors require wound rotors, and these are inevitably inferior to the solid rotor of the squirrel-cage induction motor from many points of view. Insulation is required in the slots to withstand mechanical and electrical stress, and the resulting space factor is very uneconomical, as more than 40% of the actual slot space is rarely filled with conductor. The slot depth may itself demand a somewhat larger rotor than would otherwise be required in small machines, and the cost of manufacture of a wound rotor and commutator is much greater than that of a cast rotor.

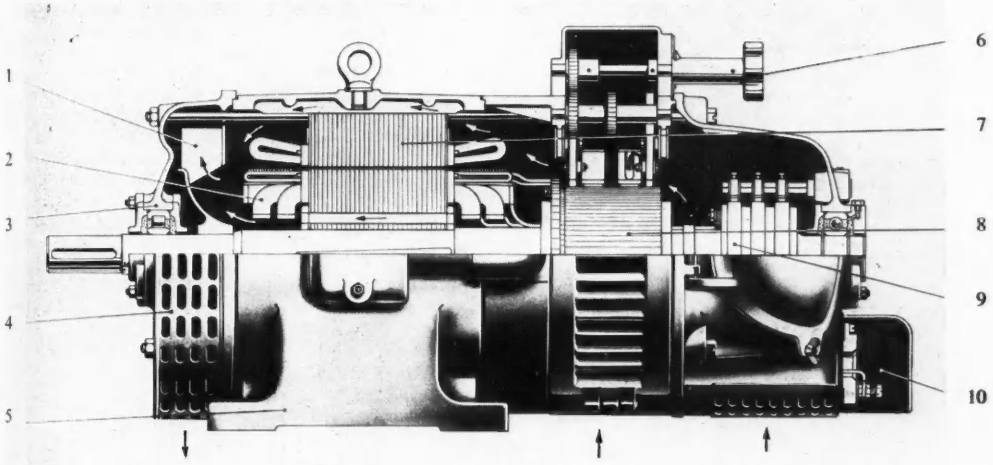

Fig. 44. **Cut-away view of a Schrage motor.** (*Courtesy of Ateliers de Construction Électriques de Charleroi.*)
(1) Cooling fan ; (2) double-wound rotor ; (3) bearing housing ; (4) guard ; (5) cast-iron frame ; (6) speed-regulating control knob ; (7) stator poles ; (8) commutator ; (9) slip-rings ; (10) terminal box.

Although it is claimed that commutation in the modern a.c. machine is as good as that in a d.c. machine, this is no indication that brush wear, sparking, and commutator maintenance are nil. There is no doubt that, if commutators could be avoided, these last three considerations alone would rule them out, but for many applications there is naturally no other alternative, obliging manufacturers of various commutator machines to compete in producing the best commutator motor for the particular requirement, with the result that an improvement in any one quality generally leads to an increased cost. The power/weight ratio of a commutator motor may be judged in comparison with that of a squirrel-cage motor by reference to Fig. 44, which shows a Schrage motor in section, the actual stator-core length being less than 20% of the overall length of the motor.

Single-Phase Motors

Although the performance of single-phase a.c. motors is generally inferior to that of corresponding polyphase motors, single-phase supply is often more readily available for domestic appliances.

The inherent properties of single-phase induction motors can be summarized as follows :—

(a) Starting torque is zero, and the motor will not start from rest without an auxiliary winding (Fig. 47), shaded poles (Fig. 48a), or purely mechanical means of imparting initial motion.

(b) Once started, the motor will run in either direction, i.e., the torque is always in the same direction as the velocity.

(c) Double-frequency components of both current and torque exist.

(d) The running-light speed is somewhat less than the synchronous speed, depending on the shape of the characteristics.

A feature of single-phase induction motors is that torque is always pulsating at a frequency double that of the supply, and speed-torque curves represent the mean level of the torque, ignoring these pulsations. Speed-torque curves of well-designed single-phase induction motors tend to have high peaks in the region of synchronous speed. The running-light speed ω_o is given by

$$\omega_o = \omega_s \sqrt{1 - (1/\tau\omega)^2} \quad . . \quad . . \quad . . \quad (6)$$

where τ is the coupled time-constant, as in eq. (5).

Speed control in a polyphase slip-ring motor by insertion of rotor resistance has already been discussed and has been shown to be an inefficient method. In the case of single-phase induction motors, addition of rotor resistance has a further effect, over and above reduction in rotor efficiency, in that the available torque is greatly reduced. The conclusion must therefore be drawn that this is a poor method of speed control.

The principle of the angled-field motor previously described, producing continuous variation in pole pitch, can also be applied to the single-phase machine. However, the possibilities of this system are as yet unexplored, although experimental models have been made to operate quite successfully. It should be remembered that single-phase induction motors can never be as efficient as polyphase motors of comparable size.

(a) Single-Phase Commutator Motors

The concept of two counter-rotating fields could be applied to single-phase commutator motors in an attempt to place them in group (*d*) in Fig. 1. A more useful and probably clearer method of explanation is to regard them as a special type of d.c. machine and to invent a rather fictitious group (*f*) into which they fit.

Reversal of the field polarity of a d.c. motor reverses the direction of rotation. Reversal of armature polarity has the same effect. Reversal of both armature and field polarities, as is obtained, for example, by reversing supply connections to either a shunt or series motor, leaves the direction of rotation unchanged. It is therefore not surprising that a d.c. machine will run when connected to a supply of alternating current. To make a satisfactory single-phase a.c. motor, however, the design must be radically changed from that of a d.c. machine, one obvious difference being that the solid stator yoke of the d.c. machine must be replaced by laminated iron. The basic diagrams for d.c. machines, discussed later, indicate that the armature coil and field coils have axes at right angles to each other and therefore no mutual inductance. Application of an alternating voltage E (r.m.s.) to the shunt field of a d.c. machine designed for E volts results in a very small current indeed, because of the inductive reactance of the winding, which will be many times its resistance. This effect is so great that it prevents the single-phase shunt a.c. motor from being an economically sound proposition at normal power frequencies. In series motors, the field carries the full line current and hence can be constructed with only a few turns. The relatively low inductance of the field winding can be tolerated in such machines, insofar as power factor is concerned. As for the rotor coil, the flux set up by the rotor, which gives rise to its inductance, is purely armature reaction flux and can thus be cancelled by a compensating winding whose axis is common with that of the rotor. The schematic diagram of the resulting single-phase compensated series motor is shown in Fig. 45, in which the armature is shown as a ring winding.

Commutation in a.c. motors is a greater problem than in d.c. motors, and particularly so in the case of single-phase a.c. machines. In Fig. 45 the coils *A* and *B* undergoing commutation at the instant shown can be seen to have their axes parallel to the main field winding. These coils receive an induced e.m.f. by transformer action and, being short-circuited through the brushes, behave like the secondary circuit of a short-circuited transformer. The short-circuit current passes through each coil for only the short interval of time it is opposite the brush, but the brush itself carries the short-circuit current continuously. If this current is not limited to a low value, the brush becomes overheated and is soon destroyed.

Interpoles, which are so effective in d.c. machines, cannot be applied in the same way in a.c. machines. Interpoles would normally be situated in the same position as the compensating winding shown in Fig. 45, and similarly connected in series with the armature. The phase of the flux produced by the interpoles would therefore be the same as that of the main field, and the e.m.f. induced in the armature coils undergoing commutation, owing to rotating through the interpole field, would be in phase with the flux. The induced voltage by transformer action is in quadrature with the main flux and is therefore incapable of being cancelled by the rotational e.m.f.

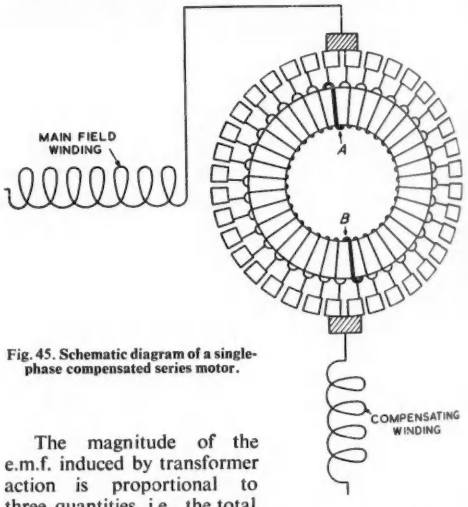

Fig. 45. Schematic diagram of a single-phase compensated series motor.

The magnitude of the e.m.f. induced by transformer action is proportional to three quantities, i.e., the total flux threading the circuit, the number of turns in the secondary, and the frequency of the e.m.f.

In the design of single-phase a.c. commutator motors, every effort is made to reduce the transformer e.m.f., resulting in the following design features :—

(1) The flux per pole is reduced by making the machine multi-polar. This has the added advantage of enabling the field reactance, which cannot be compensated to be reduced to a reasonably low value, with consequent power-factor improvement.

(2) The number of secondary turns, i.e., the number of turns between neighbouring commutator segments, is reduced to the lowest possible value, i.e., one turn. Thus, the number of commutator segments on an a.c. motor tends to be large, since the fewer the rotor conductors, the lower is the armature voltage. Even when the number of commutator segments has been increased to the largest economical number, short of using a commutator diameter bigger than that of the rotor itself, the voltage of the motor can rarely be raised above 300 V. Thus, for a large power output, the current intake must also be large. A large number of commutator segments means that each segment is very narrow. The brush area in contact with a segment must be high to carry the large current, and thus the commutator must be made long and the brushes long and narrow.

(3) In the case of high-power traction motors, the combined effect of the above two modifications is generally insufficient to produce satisfactory commutation. It should also be borne in mind that an a.c. commutator, under the worst condition, is required to switch $\sqrt{2}$ times as much current as a d.c. machine carrying the same effective current.

In traction systems in Europe the final step in the process of reducing the transformer e.m.f. to zero has been taken. This involves reduction in frequency, and a reduction from 50 to 16⅔ cps can be effected by means of two mercury-arc converters, although the wave-form of the low frequency is not ideal. The mercury-arc system will be described later.

The speed-torque characteristic of the single-phase a.c. motor is very similar to that of the d.c. series machine, tending to produce racing on light loads, but having a high starting torque. The speed control of such machines is thus largely load-dependent, as illustrated in Fig. 52, and has the advantage that the voltage input can be varied by efficient static equipment, such as an auto-transformer or variable choke.

(b) Repulsion Motors

The problem of neutralizing the reactance of the armature can be tackled in a slightly different way. A short-circuited coil on the stator (Fig. 46a) whose axis is parallel to that of the armature, will have the effect of cancelling all but leakage flux from the rotor. The rotor, as it is completely uncoupled magnetically from the main field, can be regarded as an independent circuit, and the functions of short-circuited coil and armature can be interchanged, as shown in Fig. 46b. The two stator coils can now be combined as a single coil wound on a new axis, as shown in Fig. 46c, and this is the general form of construction of the repulsion motor.

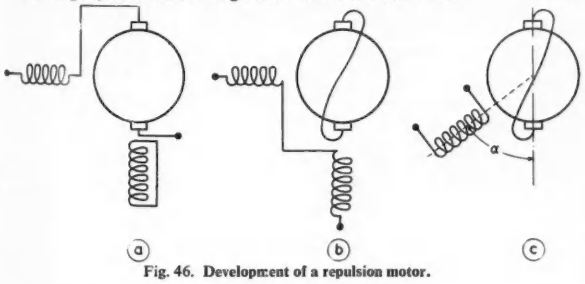

Fig. 46. Development of a repulsion motor.

Although the repulsion motor is also a series machine, it differs from the normal single-phase a.c. motor in that both the running-light speed and the speed on load are controllable by brush position. If the brushes are rotated until the angle α (Fig. 46c) is zero, the axis of the armature coil will be parallel to that of the field coil, and the machine resembles a short-circuited transformer, a large short-circuit current flowing without any torque being produced. If the brushes are in a position such that $\alpha = 90$ deg., the armature and field circuits are not coupled, and no net e.m.f. is induced in the armature, again resulting in no torque, but this time with only magnetizing current flowing in the stator. For values of α between 0 and 90 deg., torque is developed, and there is a brush position which gives optimum commutation. A fair range of speeds is possible for brush positions on either side of this optimum setting, with reasonably good commutation.

Comparative speed-regulation characteristics of two single-phase repulsion motors are shown in Table II, which is based on information supplied by The British Thomson-Houston Co. Ltd. The 1-hp motor is a type with the load-speed characteristics of a series motor, i.e., speed increases considerably with a decrease in load, while the 3-hp motor has load-speed characteristics which are substantially those of a d.c. compound-wound motor. In Table II, no-load speed is shown as a percentage of top speed at full load.

TABLE II: COMPARATIVE SPEED-REGULATION CHARACTERISTICS OF TWO SINGLE-PHASE REPULSION MOTORS.

Rating at Top-Speed Setting [hp]	Brushgear at Top-Speed Setting		Brushgear at Bottom-Speed Setting			
			2:1 speed range		3:1 speed range	
	Full-load speed	No-load speed	Full-load speed	No-load speed	Full-load speed	No-load speed
1	100%	200%	50%	180%	33%	170%
3	100%	125%	50%	115%	33%	110%

It is clear that the greater the demanded speed range, the greater will be the regulation between no load and full load at the low-speed setting. At the same time, the regulation figures are modified by the size of the machine, the larger motor having the better regulation.

While it is true that the series characteristic of this type of motor must generally result in poor speed regulation, repulsion motors have an attractive feature in that the rotor circuit is isolated from the stator, and the machine can therefore be rapidly converted to a single-phase induction motor by clamping a conducting ring around the commutator, so as to short-circuit all the windings together. Alternatively, the rotor may carry a surface d.c. winding for repulsion-motor operation, and at the same time a squirrel-cage in deep slots which automatically takes over the drive, once a low slip has been reached, in the manner of a double-cage induction motor. This enables a single-phase induction motor to be designed so that it can start up on load as a repulsion motor, converting itself either by a centrifugal switch on the rotor

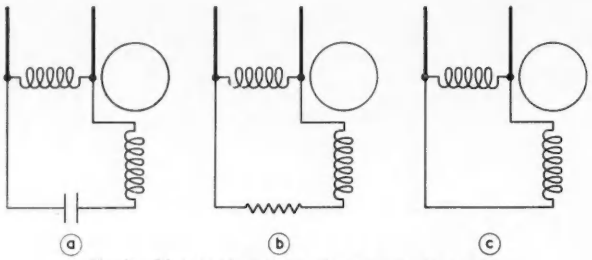

Fig. 47. Methods of starting single-phase induction motors.

with short-circuiting of the commutator once a certain speed has been reached, or by the double-cage action. Such machines are known as single-phase induction motors with repulsion start.

(c) Methods of Starting and Controlling the Speed of Single-Phase Induction Motors

One method of starting single-phase induction motors has just been described. Most other methods involve the production of a rotating component of the field sufficient to start the machine, this being effected by some phase-splitting device. Examples of some phase-splitting methods are shown in Fig. 47. In each case the principle is the same, i.e., the use of an auxiliary winding displaced in position from the main poles and carrying a current displaced in phase from that of the main field current. In Fig. 47a, use is made of a capacitor start, while in Fig. 47b a split phase is obtained by means of an extra resistance in the auxiliary field coil. In Fig. 47c, the auxiliary field coil is designed to have a different R/X ratio from that of the main field.

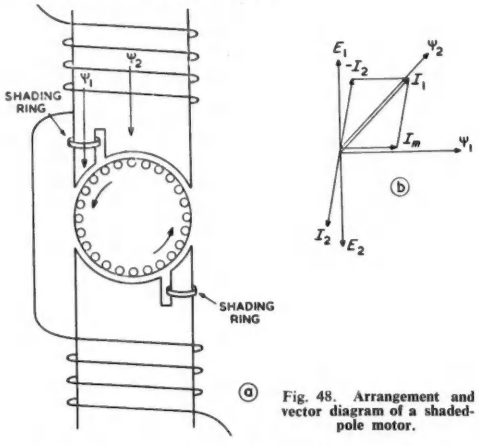

Fig. 48. Arrangement and vector diagram of a shaded-pole motor.

In some designs, the auxiliary winding is not continuously rated and is cut out as soon as the motor has attained normal running speed. In the case of the capacitor motor, shown in Fig. 47a, speed control of machines designed to run with the auxiliary winding permanently connected is sometimes effected by reconnecting the main windings from series to parallel or by tapped windings. Alternatively, an auto-transformer, or simply a resistance, can be used to vary the input voltage. This puts these motors in group (*c*) in Fig. 1, i.e., the inefficient, variable-slip class.

A further method of producing a split-phase effect is to cut slots in the pole faces and to fit short-circuited rings in the positions shown in Fig. 48. The part of the pole embraced by the "shading ring" is effectively a short-circuited transformer whose vector diagram is also shown in Fig. 48. The secondary current I_2 is almost in phase with the secondary voltage E_2, since the impedance of the ring is mainly resistive. The magnetizing current I_m sets up a flux Ψ_1. The primary current I_1 also embraces the magnetic circuit carrying Ψ_2 and is all magnetizing current insofar as this circuit is concerned. Ψ_2 is therefore in phase with I_1 and leads Ψ_1, giving rise to a field travelling from the main pole towards the shaded portion.

(d) "Universal" Motors

This class of motor, whilst listed as a single-phase a.c. motor, might also be included under d.c. machines, since the word "universal" means that it can be run equally well from d.c. or single-phase a.c. mains. Design limitations, however, are almost all concerned with its operation as an a.c. motor. The first point to note is that universal motors are only small machines, generally fractional-horsepower, and, owing to their low power consumption and output, several of the restrictions imposed in the design of single-phase a.c. commutator motors can be relaxed.

The problem of commutation is made less severe by introducing high-resistance brushes to help suppress the transformer e.m.f. in the commutated parts of the winding. The heat appearing in the brushes is not sufficient to produce damage, as the power handled is small. Being a series machine, the universal motor has a tendency towards racing on light loads, but the speed is unlikely to become dangerously high, as the total power available is absorbed in friction and windage loss before this condition is reached. Low power factor is no real disadvantage, since the amount of reactive volt-amperes necessary is very small.

Universal motors find ready application in household appliances where only a single-phase a.c. or a d.c. supply is available. Applications such as vacuum cleaners, sewing machines, food mixers, electric razors, etc. require a very small amount of power, and the single-phase universal motor is a natural choice.

Speed control is effected either by insertion of a resistance in the supply—an inefficient but cheap method, or by supplying the machine from an auto-transformer. The latter method is equivalent to supplying a d.c. series motor with a variable voltage source, as illustrated in Fig. 52. Some universal motors are designed with tapped field windings for speed control, so that, for some settings, the materials of the motor will not be run to best advantage, though at low power this is unimportant. One further method of speed control is to include a centrifugal switch on the rotor, which adds rotor resistance above a certain speed. In some motors these switches can be adjusted during operation to vary the speed.

Universal motors are usually designed so that, when connected either to alternating or direct current of the same voltage and loaded with the same full-load torque, they attain approximately the same speed. When ordering universal motors the required direction of rotation should be stated, as reversal may perhaps be possible only by changing an internal connection, if the field and armature are joined inside the frame.

D.C. MAINS - INPUT DRIVES

D.C. Motors

Variations in the speed of d.c. machines can be effected by varying flux density or the e.m.f. applied to the armature. Permanent-magnet motors have only the latter alternative. When a load torque is applied to the rotor, the first reaction of the motor is to slow down, causing the back e.m.f. E_b to be reduced, and more current I_a to flow in the armature. It is this current, acted on by the field, which produces the torque necessary to balance the load torque. When this state of balance is reached, the applied e.m.f. E_a is opposed by the back e.m.f. E_b and the resistance drop R in the armature conductors, so that

$$E_a = E_b + I_aR \quad .. \quad .. \quad .. \quad .. \quad (7)$$

Therefore,

$$E_aI_a = E_bI_a + I_a^2R \quad .. \quad .. \quad .. \quad (8)$$

E_aI_a is clearly the power input. I_a^2R is the rotor copper loss, and hence E_bI_a is the output, including friction and windage losses.

For a fixed flux density, E_b is proportional to speed. Eq. (7) shows, therefore, that, for a fixed flux density, the speed regulation on load is proportional to R; in other words, a high-resistance rotor will give rise to considerable loss of speed when load, causing I_a to flow, is applied.

One effect has been neglected in the above discussion. When rotor current is flowing, the rotor itself acts as an electromagnet and tends to distort or cancel the air-gap flux, this effect being known as armature reaction. The speed drop on load therefore tends to differ from that calculated from eq. (7) if nothing is done to counteract the effect. So far, however, only permanent field-magnet machines have been considered. When the field is supplied by electromagnets the characteristics depend mostly on how the field and armature circuits are relatively connected.

In Fig. 49, the field and armature are in series. Neglecting armature reaction for the moment, $E_a = E_b + I_aR + E_f$, the field voltage E_f being the product of field resistance R_f and I_a. Thus,

$$E_a = E_b + I_a(R + R_f) \quad .. \quad .. \quad .. \quad (9)$$

However, E_b is itself proportional to I_a (since I_a produces the field flux) and to the speed ω, so that eq. (9) becomes

$$E_a = k\omega I_a + I_a(R + R_f) = I_a(R + R_f + k\omega) \quad .. \quad (10)$$

Torque T is proportional to the product of flux density and armature current, i.e., $T = k_1I_a^2$. Hence,

$$E_a = (R + R_f + k\omega)\sqrt{T/k_1} \quad .. \quad .. \quad (11)$$

With a fixed supply voltage, torque T is a maximum when $\omega = 0$, while, for very small values of T, ω is very large. The general form of eq. (11) for series motors, in terms of T and ω, is also shown in Fig. 49.

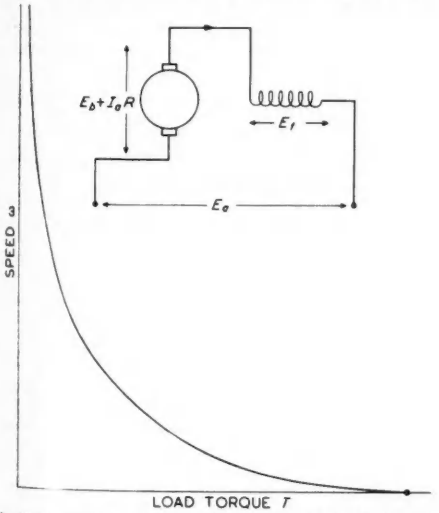

Fig. 49. External characteristics of d.c. motor with field and armature in series.

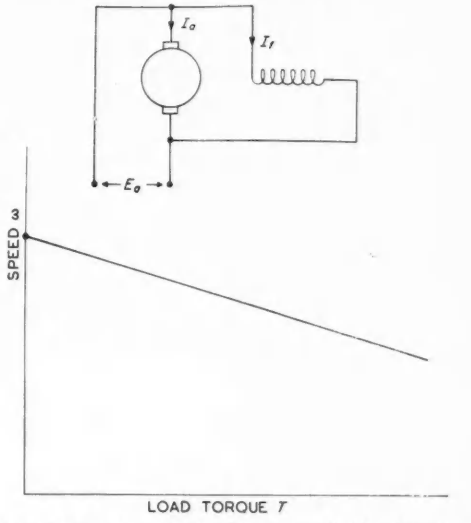

Fig. 50. External characteristics of d.c. motor with field and armature in parallel.

In Fig. 50, the field and armature are in parallel, i.e., shunt-wound. Again neglecting armature reaction, the motor field current I_f is constant, and the back e.m.f. E_b is given simply by $k_2\omega$, so that

$$E_a = k_2\omega + I_aR$$

also,

$$T = k_3I_a$$

and hence

$$E_a = k_2\omega + TR/k_3 \quad .. \quad .. \quad .. \quad (12)$$

The general form of eq. (12) for shunt-wound motors, in terms of T and ω, is also shown in Fig. 50.

In normal d.c. machines the flux enters the armature via one set of poles and returns via another.* The armature conductors are therefore concerned with crossing alternate poles of opposite sense and, if unidirectional torque is to be obtained, the armature current must be suitably switched or commutated. In the case of d.c.

* The exception is the homopolar machine, which, however, has limited application, as it can be used only on very low voltages.

machines the commutator may be regarded as converting the alternating back e.m.f. of each armature conductor from the frequency at which it is generated (depending on the rate of crossing poles) to zero frequency. A developed diagram of a d.c. armature with commutator is shown in Fig. 51a, in which the current flows through the armature coils into the brush through the segment *B*. After a small interval of time, the commutator segments have moved until the brush bridges a pair of segments, *B* and *B'*, as shown in Fig. 51b, and a little later on the conditions are as shown in 51c. It can be seen that in the time interval between which segments *B* and *B'* are in contact with the brush, the current in coil *A* has been reversed. The coil *A*, like all the other coils, is inductive, and the current in it does not immediately reduce to zero when short-circuited by the brush, as in Fig. 51b, even if the induced e.m.f. is zero at that instant. If the current has not succeeded in reversing by the time the brush leaves segment *B*, an arc occurs, burning both brush and segment. Field distortion due to armature reaction aggravates the problem of commutation.

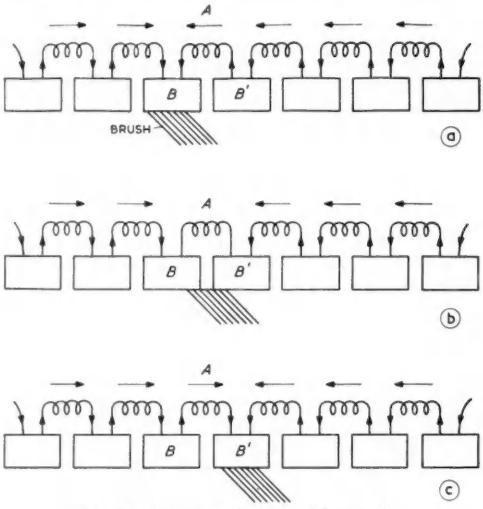

Fig. 51. Commutation in a normal d.c. machine.

The usual solution is to employ between the main poles auxiliary field poles which are energized by windings in series with the armature. The effect of these interpoles or commutating poles is to neutralize armature reaction and to provide enough induced e.m.f. in the armature coil undergoing commutation to ensure that the correct current is flowing immediately prior to the brush leaving the appropriate segment.

Speed Control of D.C. Series Motors

The speed-torque characteristics of the series motor (Fig. 49) show that speed is very largely load-dependent. Eq. (11), however, shows that torque is proportional to the square of the applied voltage for any given speed. Fig. 52 shows how the characteristic is affected by a reduction in supply voltage from E_a to $E_a/\sqrt{2}$. A motor running at a speed ω_1 with applied voltage E_a against a fixed load torque will slow down to a speed ω_2 when the voltage is reduced to $E_a/\sqrt{2}$. The power output is reduced in the ratio ω_2/ω_1, but the efficiency is little affected, provided that a variable source of applied voltage, such as a generator, is available. If the source voltage is fixed, speed control can be effected by insertion of a series resistance. It should be remembered, however, that this is an essentially wasteful system. The action of the series resistance is to cut down the machine terminal voltage, at the same time converting the surplus power into heat in the control resistance itself. The power input from the mains is virtually unchanged.

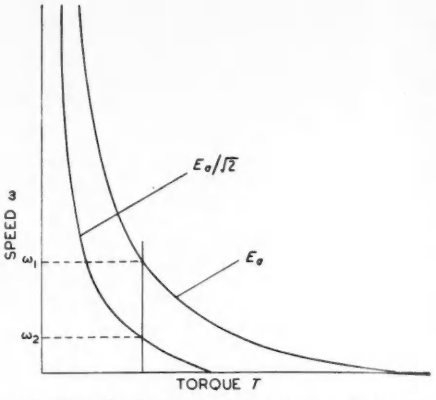

Fig. 52. Effect of reduction in supply voltage on the speed-torque characteristics of a d.c. series motor.

An alternative control system for a fixed voltage supply is to provide a variable resistance which shunts the armature. This also is merely a means of extracting power from the armature and dissipating it in the control resistance. A combination of series resistance and armature shunt resistance may also be used.

Methods of control of this type, in which the extra power is dissipated in a rheostat, are naturally wasteful; however, where power consumption is of secondary importance, they have the advantage of providing cheap and convenient speed regulation, and a wide range of control equipment for the purpose is available.

Speed Control of D.C. Shunt Motors

If speed is changed by varying the field current, eq. (12) for shunt motors is modified to include the effect of changes in the motor field current I_f. Thus, the back e.m.f. E_b is no longer given by $k_2\omega$ but by $k_4 I_f \omega$, and the torque T is now equal to $k_3 I_f I_a$. Thus,

$$E_a = k_4 I_f \omega + I_a R$$

or, in other words,

$$\omega = \frac{E_a}{k_4 I_f} - \frac{TR}{k_4 k_3 I_f^2} \quad .. \quad .. \quad .. \quad (13)$$

so that $k_4 I_f$ replaces k_2, and $k_3 I_f$ replaces k_3.

If the field current is cut by 50%, the values of k_2 and k_3 in eq. (12) are effectively halved; the resulting speed-torque curve for the half-field-current condition is shown in Fig. 53a compared with the speed-torque curve for full field current. The running-light speed is doubled, but the slope of the line is increased by 4, i.e., speed regulation is increased by 4. Thus, although field weakening apparently increases speed without incurring extra power loss, the loss of torque results in poor speed regulation at the higher speed and a reduction in available power output. A further disadvantage of this system is that fine control of speed is difficult at high speeds because of armature reaction effects coupled with a very weak field.

A second method of speed control is obtained by varying the armature voltage by inserting a resistance R_a in series with the armature, and at the same time keeping the field current constant. Eq. (12) is modified to the extent that R is replaced by $(R + R_a)$, and Fig. 53b shows that the slope of the speed-torque curve is doubled and the running-light speed virtually unaltered. This, in fact, is not a good method, since it controls speed only as the result of load torque, and the reduced power output resulting from the reduced speed does not in turn result in a reduced power input. The armature series resistance

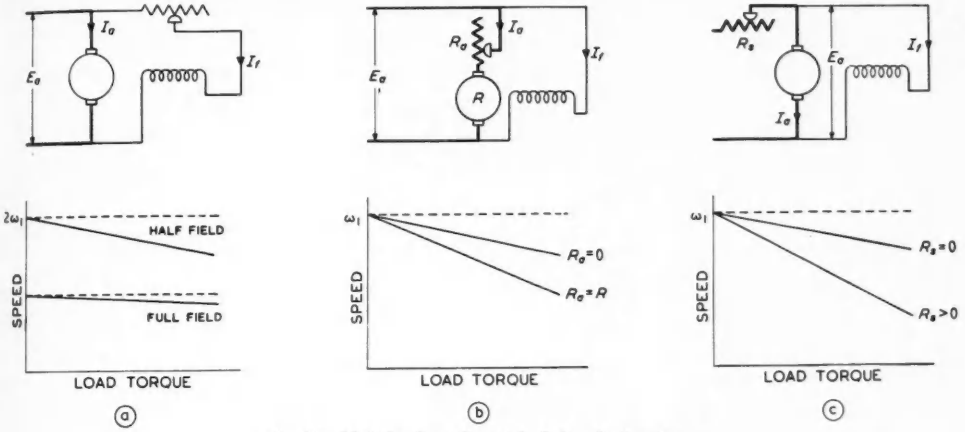

Fig. 53. **Methods of speed control of d.c. shunt motors.**

R_a consumes power $I_a^2R_a$ compared with the output E_bI_a, the total power being

$$(E_b + I_aR)I_a = I_aE_a$$

i.e., the same as the power consumed before speed reduction. The efficiency, therefore, decreases with a reduction in speed; for some applications, this may not be a serious limitation, as it is generally preferable to a system having a drop in efficiency as speed is increased.

A third method of speed control, illustrated in Fig. 53c, involves the insertion of a resistance R_s in series with the motor. This cuts down both the effective values of E_a and I_f in eq. (13) and again results in an increased slope of characteristic rather than a reduction in running-light speed. The slope is now increased by the square of the effective voltage reduction. The available power is reduced in a similar manner to that resulting from field-resistance insertion.

None of the methods illustrated in Fig. 53 is satisfactory from both the point of view of efficiency over the speed range and available power output. Permanent-magnet motors can only employ the method shown in Fig. 53c.

Speed Control of Separately Excited D.C. Motors

The best method of d.c. speed control is certainly achieved by efficient control of armature current without a change in field current. Efficient control means that the voltage applied to the armature must be controllable without recourse to a series resistance. The result of such control simply reduces the effective value of E_a in eqs. (12) and (13) and results in a general shifting of the speed-torque line without a change of slope (Fig. 54). Incidentally, in a.c. systems of speed control appearing as (*g*) and (*h*) in the classification in Fig. 1, this type of control is used, and descriptions of the methods of obtaining a variable voltage for the armature circuit are given later in connection with these particular systems.

Speed Control of Compound D.C. Motors

The field of a compound motor is set up by two separate sets of field coils, one set being in series and the other set in parallel with the armature. If the shunt field is in parallel with both armature and series field coils, as shown in Fig. 55a, the motor is said to be of the long-shunt type. In the short-shunt type shown diagrammatically in Fig. 55b, the parallel coil is connected directly across the armature.

The two sets of coils can be connected in the same sense, so that the armature current through the series coils produces a field which assists that produced by the shunt field. Such a motor is said to possess cumulative compounding. A machine in which the fields are opposed

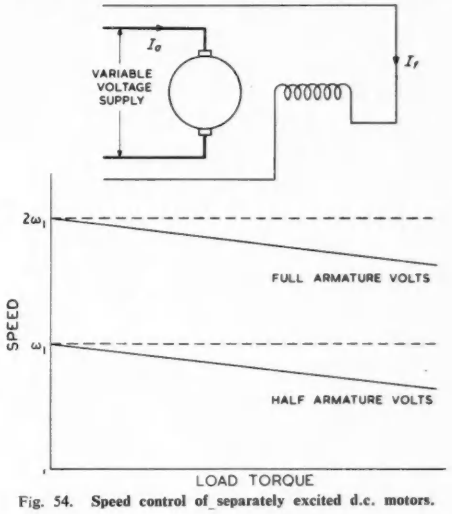

Fig. 54. **Speed control of separately excited d.c. motors.**

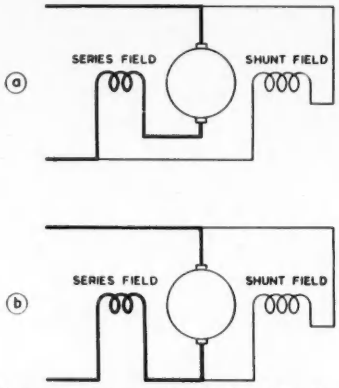

Fig. 55. **Compound motor connections, showing (a) long-shunt type, and (b) short-shunt type.**

to each other is called a differentially compounded machine.

A cumulatively compounded motor has characteristics which represent some intermediate stage between a shunt and a series motor, depending on the relative strength of the fluxes produced by the two sets of coils. If the machine is regarded primarily as a shunt motor, the application of load, causing armature current to flow, produces a stronger field and reduced speed, as in a series motor. Typical speed-torque curves for a cumulatively compounded motor are shown in Fig. 56a. The greater the ampere-turns of the series field relative to those of the shunt field, the greater is the speed drop on load, i.e., the nearer the machine approaches a pure series motor. The dotted curves in Fig. 56a show the characteristics of a shunt motor and a series motor for comparison. Fig. 56b shows the type of speed-torque characteristics resulting from differential compounding, where the shunt field contributes the major part of the flux and the series field is used as a minor adjustment for the slope of the characteristic. Armature current flowing through the series coils weakens the field and tends to cancel the effect of the armature *IR* drop.

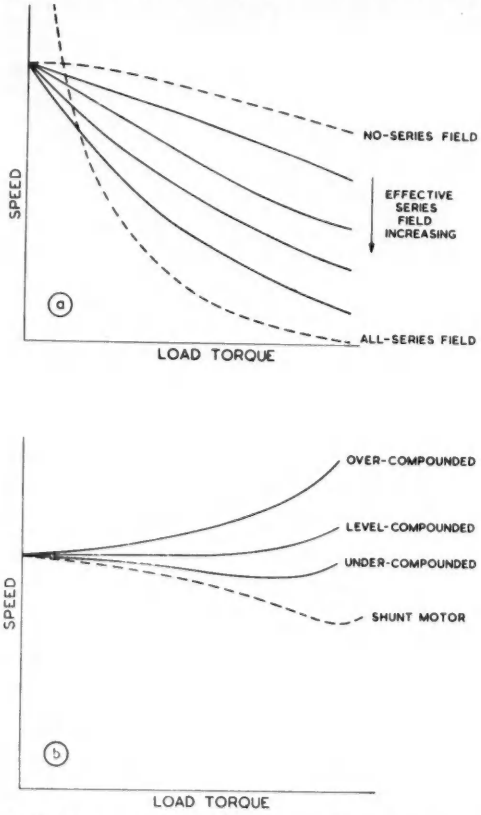

Fig. 56. **Speed-torque characteristics of (a) a cumulatively compounded and (b) a differentially compounded d.c. motor.**

As the amount of series field is increased, a stage can be reached where the speed-torque characteristic is virtually horizontal, tending towards a machine with constant speed at all loads. It should be remembered, however, that the speed will eventually rise with very large loads due to the armature reaction effect, giving a tendency to instability, unless the speed-torque characteristic of the load rises rapidly. Another point to be borne in mind is that level compounding does not *guarantee* a fixed speed in the same way as does a servo-controlled d.c. motor.

Almost all the combinations of speed control used in connection with shunt or series motors can be applied to compound machines. The complexity of the system, however, makes the prediction of performance very difficult. If the speed-torque curve for one particular control setting is designed to be acceptable, then it will in general be unacceptable at another control setting. For example, a differentially compounded motor employing a long shunt and using resistance in the shunt field as a means of speed control might be designed to have level compounding at bottom speed. If the shunt field is weakened to cause a speed increase, the series field has a greater effect and over-compounding and possible instability results at the higher speed settings. Alternatively, if the set is designed for level compounding at top speed, the machine will be virtually a shunt motor at bottom speed.

Clearly, space does not permit a discussion of all the many possible combinations of inserting shunt and series resistances in compound machines for the purpose of speed control, and it is advisable to consider each case on its merits.

Utilization of D.C. Motors

The d.c. machine is at present the commonest form of variable-speed motor, despite the fact that an a.c. supply is usually the only one available. As a matter of fact, one of the advantages of the d.c. machine is that it is a standard piece of equipment which is usually available from stock, and this may lead to a certain amount of encouragement to customers to install d.c. machines for applications where an a.c. motor might be more advantageous. It must be remembered that, unless a d.c. mains supply is available, installation of a d.c. machine involves the conversion of a.c. to d.c. at the full power level by some other machine, whether it be rotary or static. Some of the systems employing d.c. machines fed from rotary machines involve an a.c. motor as the prime mover; discussion of the various a.c. mains systems which utilize a d.c. motor as the final drive is included in the following section.

SYSTEMS CONVERTING MAINS A.C. TO D.C.

The basic theory of speed control in d.c. machines has already been discussed, and it is apparent that the best arrangement for speed control involves changing the armature voltage. In this way the back e.m.f. can be adjusted without field weakening, which always results in poor speed regulation at high speeds. The problem of economic speed control is therefore converted into a problem of economic voltage control. Since alternating current is usually more readily available, the alternative schemes are clearly as follows :—

(i) Generation of direct current, the generator being driven by a constant-speed a.c. machine and voltage variation effected by control of the generator field current, i.e., Ward-Leonard systems.

(ii) Rectification of the alternating current, variable voltage being produced either on the a.c. side or in the process of rectification.

All motor-generator sets are included in (i) above, which is effectively group (*g*) in Fig. 1. Group (*h*), which is the same as (ii) above, includes the following types of rectification and control :—

(a) Mercury arcs.

(b) Electronic valves of various types.

(c) Metal rectifiers, with or without magnetic amplifiers.

Systems in group (*f*) have already been discussed in connection with single-phase commutator motors, and are not included in this section.

(a) Ward-Leonard Systems

A schematic diagram of a Ward-Leonard system of control is shown in Fig. 57, in which the fields of the d.c. machines are supplied by an exciter driven from a constant-speed motor. The armature voltage supplied to the final drive motor is controlled by a centre-tapped potentiometer in the generator field circuit, the centre tap implying that reversal of polarity resulting in reversal of the direction of drive is possible. The basic disadvantages of such systems are the following :—

(1) It is necessary to provide three machines, each capable of handling the full power supplied to the load. A small exciter is also required.

(2) Maintenance of brushgear and commutators on three machines is required.

On the other hand, their advantages are :—

(1) A large speed range with good regulation and fine control is available.

(2) Rapid reversal of direction of rotation is possible.

(3) Regenerative braking is possible.

(4) Standard machines, which are ordinarily manufactured for individual use, are used in the system.

All the machines may be mounted on a single bedplate, or the final drive motor may be mounted separately. This latter alternative offers a further advantage in that the power/weight ratio of the final drive motor is high, even though that of the set as a whole is low. This can be important in certain applications where the final drive motor forms part of a moving system whose weight must be minimized. In applications where very wide speed ranges are required, field weakening may also be employed in the final drive-motor circuit. Although the prime mover in Fig. 57 is shown as an induction motor, it need not be an electric motor at all, but could be an internal combustion engine, turbine, etc., although the a.c. mains supply is often the most convenient source of energy.

To save initial cost, a few systems are made with self-excited motor and generator, but these are generally inefficient and limited in output. They are not reversible in the manner of the basic system shown in Fig. 57, and their speed regulation is poor. Nevertheless, such systems are sometimes used, either with two series machines or with two shunt machines.

Although the reversal of rotation in Fig. 57 is shown as being the result of changing field polarity on the generator, reversal of polarity on the final drive-motor field is equally effective. If rapid reversal is required, switching of either the motor or generator field may be insufficient to meet requirements. The field circuits are highly inductive, and mere reversal of applied voltage does not produce sudden reversal either of current or flux. In this case the armature connections must be reversed, at the expense of a much larger and more expensive reversing contactor, capable of handling the much larger armature current.

Although regenerative braking is possible, it is often supplemented by dynamic unregenerative braking obtained by connecting a resistor across the final drive-motor armature for the last part of the deceleration.

The lowest speed obtainable with the basic Ward-Leonard set is fixed by the level of the residual magnetism in the generator, since this will still produce an e.m.f., even when the generator field current is cut to zero. Modifications to permit very low speeds to be obtained are based on two principles, i.e., (a) a counterwinding which can produce field ampere-turns in opposition to the main field, which are just sufficient to cancel the residual flux when the main field is cut to zero ; and (b) a switching device, enabling the generator armature to be connected across its own field as the latter is disconnected from the exciter. The connection is such that the armature voltage causes current in the field circuit which kills the existing flux. This is often known as the "suicide" connection.

Exciters :—

In very large Ward-Leonard sets the exciter is itself quite a large machine. The rotary exciter can, of course, be replaced by any other device capable of providing a d.c. voltage for the field circuits. There are several types of exciters, i.e., (1) rotary, (2) electronic, (3) metal rectifier, (4) electronic amplifier, (5) magnetic amplifier, and (6) rotary amplifier.

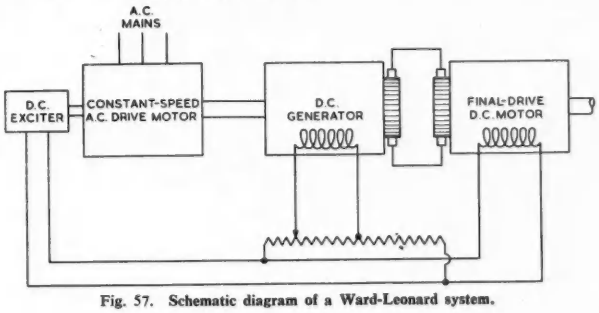

Fig. 57. Schematic diagram of a Ward-Leonard system.

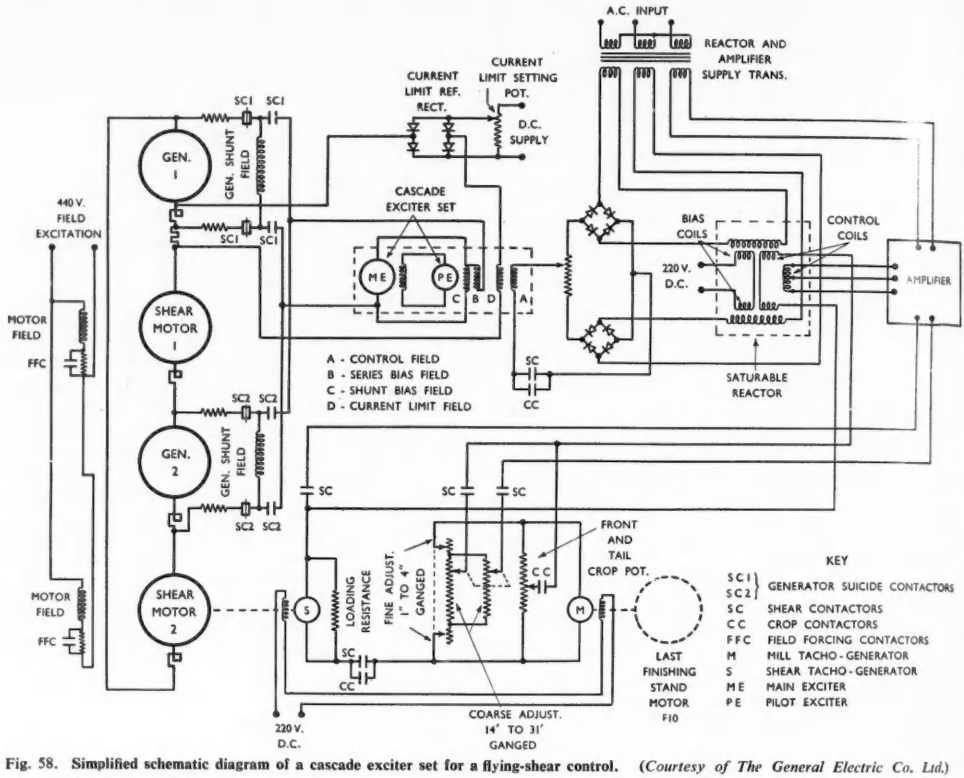

Fig. 58. Simplified schematic diagram of a cascade exciter set for a flying-shear control. (*Courtesy of The General Electric Co. Ltd.*)

The advantages of rotary exciters are low cost, together with the ability to continue supplying field current for several seconds in the event of a power failure of short duration.

The advantages of the electronic exciter are its low weight and its easy adaptation to servo-controlled systems, but it has the disadvantage of requiring a warm-up time prior to starting. Metal rectifiers are similar in most respects to electronic systems, without the necessity for a warm-up period, but they generally have a lower efficiency than the corresponding electronic exciter.

Amplifier-type exciters are used for three main reasons. The first is that, when field excitation is to be reduced, increased power-conversion efficiency is obtained ; the second reason is that the controls can be much smaller when they are not operating in the actual field circuit, and finally, better automatic control is possible with such a system. The amplifiers can be used independently on motor and generator.

A normal d.c. machine can be regarded as an amplifier, since control of a small amount of power in the field results in control of a large amount of armature power. Such rotary amplifiers as amplidynes and metadynes are simply two stages of amplification built into one machine. Magnetic amplifiers operate on the principle that, if the iron of a transformer is near to saturation, small changes in d.c. excitation will have profound effects on its operation as a transformer. This type of amplifier is very robust and reliable.

A great deal of work has gone into the development of exciters for use with Ward-Leonard systems. It has been claimed that almost any drive requirement can be fulfilled with the use of servo-controlled Ward-Leonard sets. Whilst this may be true, the complexity of the resulting equipment may be very high, resulting in higher cost, higher maintenance, less reliability, etc., so that these factors must be taken into consideration when contemplating such a variable-speed system.

Ward-Leonard drives are certainly one of the most popular variable speed systems at the present time and are manufactured with a wide variety of exciter and control systems. The complexity of some of these control systems rivals that of electronic computing-machine circuits. Fig. 58, for example, is a schematic diagram of a cascade exciter set for a flying-shear control. In such systems fault-finding is clearly the job of the specialist, a factor which must offset some of the advantages.

Many Ward-Leonard sets, with wide variations in principle and layout, are commercially available to-day. Thus, to mention only a few, such sets are produced in England by Metropolitan-Vickers, the General Electric Co., British Thomson-Houston, and The Electric Construction Company. Of these, the General Electric set uses an electronically operated cascade exciter system, the British Thomson-Houston set uses exciters operated by vacuum-valve circuits, and the Electric Construction Company set uses purely electronic exciters. In Switzerland, Oerlikon uses exciters operated by servo-controlled motorized rheostats, while Brown Boveri uses four exciters, two of which are operated directly by rheostat control and the other two via magnetic amplifiers. In Belgium, A.C.E.C. has thyratron circuits operating

directly into the motor and generator field circuits. In the U.S.A., the " VS " type of Ward-Leonard set produced by the Reliance Electrical & Engineering Co. uses thyratrons operating directly on the motor and generator fields, while the General Electric " Packaged Speed Variator " features amplidyne exciter control of the generator or motor field, and the " Select-Spede " produced by the Louis Allis Co. uses a magnetic amplifier operating directly on the generator field, the motor field being fed from a metal rectifier. In the " Life-Line " adjustable-voltage drive, manufactured by the Westinghouse Electric Corporation, a selenium rectifier is used to supply power to the fields of both the d.c. generator and d.c. motor.

The examples given above are, as already stated, only a few of the Ward-Leonard sets at present commercially available, and, indeed, are not necessarily the only type of Ward-Leonard system produced by the particular firms mentioned. It can therefore be appreciated how important it is for those contemplating a system of this type to obtain full relevant information, if the optimum arrangement for a particular requirement is to be obtained.

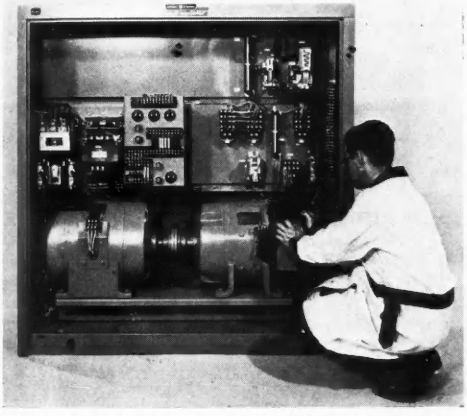

Fig. 59. " Speed Variator " packaged variable-speed power unit. (*Courtesy of General Electric Company, U.S.A.*)

Many of the sets of equipment supplying the direct current to the final drive motor are " packaged ", as shown in Figs. 59 and 61. The size and cost of this equipment must all be tolerated by the customer before he buys the actual motor which is to do the job. Thus, all the equipment shown in Figs. 59 and 61 is, so to speak, " auxiliary " to the driving motor, whose size is no bigger than the components of the motor-generator sets in the lower half of the package. The fact that so many manufacturers develop complex control schemes is an indication that there is a demand for very accurate speed control. Many of the systems, in fact, incorporate servo-mechanisms, and the fact that the Ward-Leonard system lends itself readily to servo-systems may account in large part for its popularity.

A 4700-hp Metropolitan-Vickers electric winder with a twin d.c. Ward-Leonard drive, installed at the main shaft of the West Driefontein Gold Mining Co. Ltd., South Africa, is shown in Fig. 60.

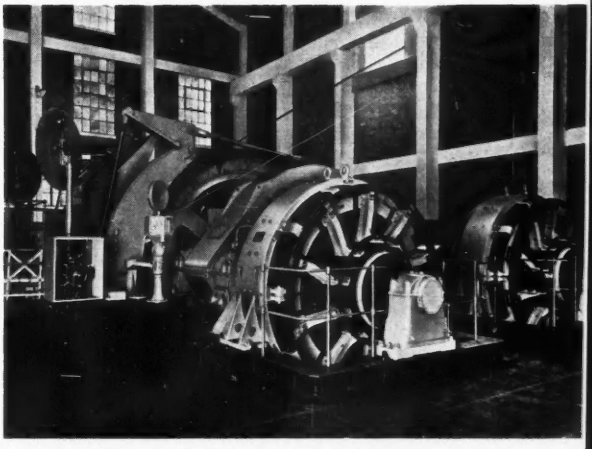

Fig. 60. 4700-hp electric winder with a twin d.c. Ward-Leonard drive, installed in a gold mine. (*Courtesy of Metropolitan-Vickers Electrical Co. Ltd.*)

(b) Motors Driven by Mercury-Arc Rectifiers

The mercury-arc rectifier is a compact and efficient method of converting alternating to direct current, or direct to alternating current. When used for the latter purpose, it is usually called an inverter. The device consists of an evacuated bulb into which a pool of mercury is introduced, the space inside the bulb therefore being filled with mercury vapour. A number of anodes projects into the bulb, the whole arrangement constituting in its simplest form a gas-filled diode, in which, as the mercury pool is the cathode, conventional current flow is towards the pool. A simple rectifier circuit using two anodes is shown in Fig. 62a, the resulting current form being shown in Fig. 62b. Current flow is always from the positive anode, and full-wave rectification is obtained. Whilst the

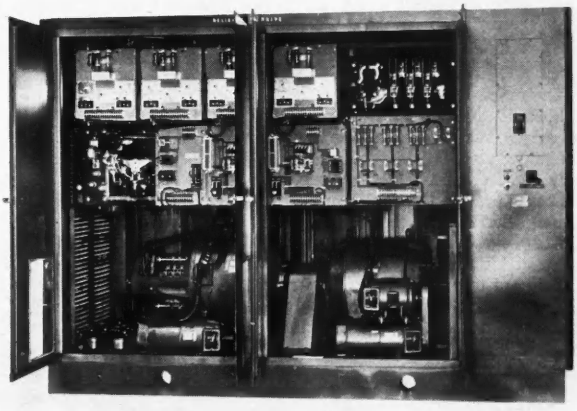

Fig. 61. Packaged variable-speed drive system. (*Courtesy of Reliance Electric and Engineering Co.*)

output current is unidirectional, it is not what is usually meant by " direct " current, the output wave-form consisting of a steady current together with numerous harmonics of the original a.c. wave-form. In electronic amplifier power-packs, double-diode rectification of this type is usually adequate, the unwanted a.c. components being eliminated by *RC* or *LC* smoothing circuits. For large power, the smoothing components needed would be large and expensive and would result in lower running efficiency. A much better approximation to a steady output current can be obtained by using more phases, a six-phase system being shown in Fig. 63a. The current flows from the most positive anode, and the resulting output wave-form shown in Fig. 63b is clearly superior to that in Fig. 62. The penalty incurred in this case is a 3:6 phase transformer to supply the anodes, but this is not as costly as it might appear, since the input voltage will generally need a step-down transformer in any case, if high-power motors are involved and current is being taken from the grid. For even better output wave-forms, a 12- or even 24-phase rectifier can be used.

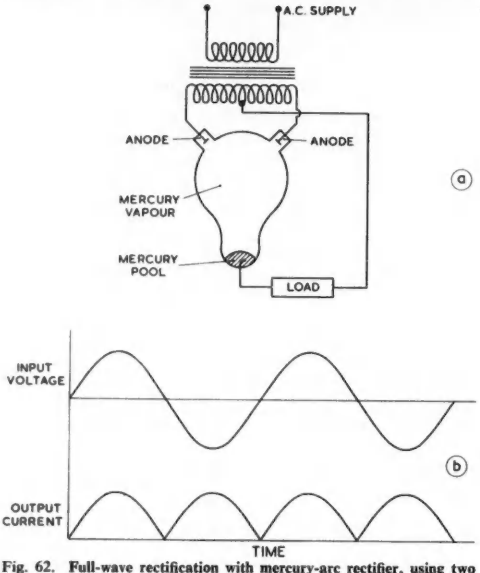

Fig. 62. Full-wave rectification with mercury-arc rectifier, using two anodes.

The function of the mercury vapour in the bulb is to enable much greater current to flow than would be possible using a vacuum valve. The initial flow of anode current immediately following switching on, results in the gas being ionized, and the valve is said to be " struck ". Unlike a vacuum valve, once current is flowing, it cannot be controlled by the use of a third electrode or grid. A grid can, however, control the value of anode voltage necessary for the valve to strike, and this phenomenon can be used to control the output current of a rectifier, the method employed being as follows :—A grid is fitted to control each anode of the rectifier separately. The grids are biased negatively, but are connected in series with " peaking transformers ", which are small transformers connected to a supply voltage which saturates the iron in them, causing the secondary voltage to consist of short pulses, alternately positive and negative. The positive pulses serve to neutralize the bias and allow the anode

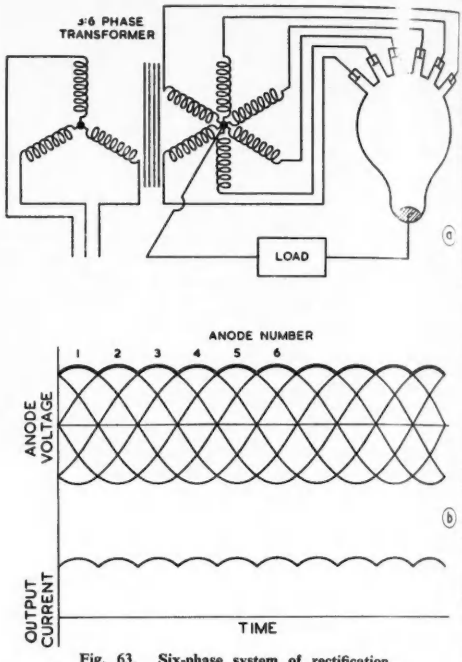

Fig. 63. Six-phase system of rectification.
The thick line indicates the current-carrying period.

to strike ; by altering the phase of the input e.m.f. to the peaking transformers the time of striking can be varied.

The effect of grid control on output current is shown in Fig. 64. Whilst the mean level of the output is varied, the wave-form suffers considerable distortion, the degree of which becomes worse with lowered mean level. Furthermore, the rectifier has a tendency to reverse the procedure and to superimpose distortions on the voltage

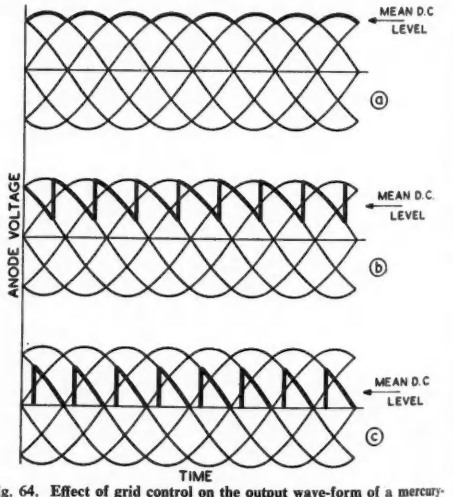

Fig. 64. Effect of grid control on the output wave-form of a mercury-arc rectifier.
(a) No grid control ; (b) striking delayed by grids ; (c) result of further delay in striking.
The thick lines indicate the current-carrying periods.

wave-form of the main supply, the magnitude of the effect depending on the relative impedances of the load and the supply busbars. The power factor of the system is good when no grid control is applied, but falls almost proportionally with the reduction of voltage by grid control. A preferable control system from the point of view of wave-form and power factor is to vary the input a.c. supply. This may be effected in one of two ways, as follows :—

(a) Tap-changing gear may be included on the anode-feeding transformer. Such a system provides a number of speeds without the facility for continuous speed variation. It is therefore comparable with pole-changing induction motors, except that the increment between steps can be much smaller and the number of possible steps much larger in the case of the rectifier-driven machine.

(b) A special type of variable-voltage transformer or an induction regulator can be used to feed the anodes. This system, whilst providing continuous variation, is obviously more costly. The total equipment consists of a voltage regulator, mercury-arc rectifier, and d.c. motor, all capable of handling full power. From the point of view of cost and total bulk, this system is comparable with a Ward-Leonard system.

The use of the mercury-arc converter for inversion will now be considered. By the nature of this equipment, current can only flow from anode to cathode, so that, if the power flow is to be changed, the voltage polarity must be reversed. When the mercury-arc converter is used to drive a d.c. motor, regenerative braking is possible only if the back e.m.f. of the motor is reversed with respect to the rectifier voltage. This can be achieved by the use of two rectifiers coupled " back-to-back " in what is known as the " figure-of-eight " connection.[6] In this case, transition from motoring to generating takes place smoothly, but the penalty is the use of two rectifiers instead of one, and the advantage does not generally warrant the cost. Alternative schemes involve reversing either the motor armature or the field connections and using a single rectifier in what is known as the " O " connection. Of the two, field reversal presents the problem of the field time-constant, whereby the flux can be changed rapidly only by field-forcing, involving special design of the motor. Armature reversal can be achieved more rapidly at the expense of a much heavier contactor to break the larger current.

Reference has already been made to the use of mercury-arc converters as frequency changers, to step down from 50 to 16⅔ cps to supply single-phase commutator machines used as traction motors. In this application two 6-phase rectifiers are connected back-to-back, to drive what is effectively direct current first in one direction and then the other through the load. If each anode carried the same voltage the resulting wave-form would be poor, as shown in Fig. 65a, but by suitable design of transformer a shaped wave-form, such as that shown in Fig. 65b, is obtained, since the nature of the 3:1 conversion is such that the same anode carries current at the same period in each cycle.

The voltage drop in the arc of a mercury-arc converter is of the order of 25 volts and is independent of the current. The efficiency of the device when operated without grid control is therefore simply given by $V/(V+25)$, where V is the d.c. output voltage. Consequently, efficiencies of well over 90% are easily obtainable. The power loss in the rectifier appears as heat, and a cooling fan is usually necessary in medium- or high-power installations. The rectifiers are either of the glass-bulb or steel-tank type. In some, the bulb is sealed off, whilst in others it is continually pumped out. Whilst the latter type can theoretically be in service indefinitely, the extra cost of pumping equipment offsets the advantage of the maintenance of a high vacuum.

In the English Electric excitron-operated controller, which is available for powers between 25 and 50 hp, the a.c. mains voltage is fed via a transformer to three single-anode mercury-arc rectifiers, where it is converted to a d.c. voltage which is then applied to the motor armature, any variation of this applied voltage effecting a corresponding variation in motor speed. A proportion of the armature terminal voltage is compared with a preset reference voltage. The resulting voltage difference is then applied

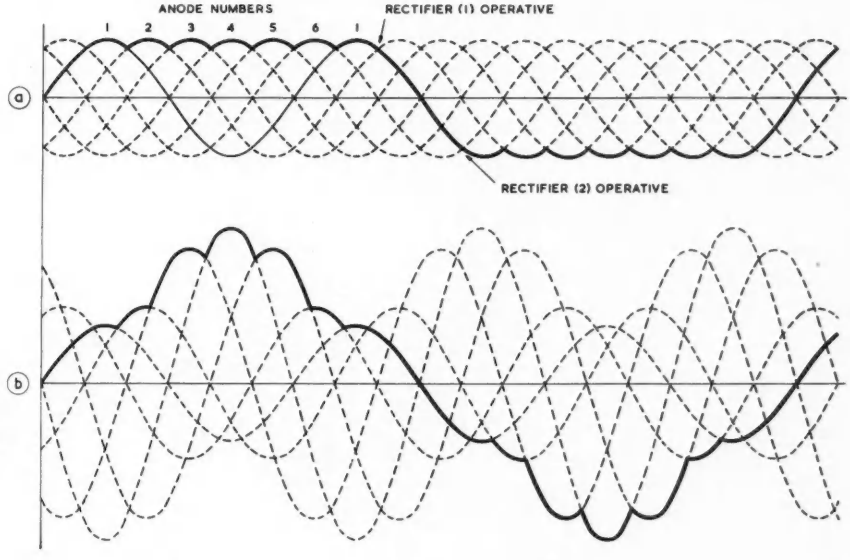

Fig. 65. Mercury-arc conversion from 50 to 16⅔ cps. The thick lines show the resulting 16⅔-cps waveforms.

to the grids of the rectifiers as the d.c. signal, so that any change in the armature terminal voltage alters the value of this d.c. signal and thus corrects the output from the rectifiers. Consequently, a closed-loop control is formed. Metal rectifiers are used for supplying the motor field. The complete equipment required comprises a d.c. shunt-wound motor, rated for the load and speed change desired, a control cubicle containing the mercury-arc rectifiers and metal rectifiers, control and protective relays, armature contactor, control circuits and relays, a transformer supplying the mercury-arc rectifiers, a series armature choke for improving commutation and reducing motor losses, and a control station, with speed-setting potentiometer and push-button controls.

Mercury-arc rectifiers are compact and reliable. They have, for example, been used as pit-winder drives in sizes up to 4500 hp. Fig. 66 illustrates the relative sizes of components in a grid-controlled system made in the U.K. by the Nevelin Electric Co. Ltd. and used in their Lancashire-Nevelin " Varionic " drive. The rectifier equipment delivers controlled d.c. power to the armature of a d.c. motor, and motor speed may be adjusted manually by a handwheel or by a push-button at local or remote stations, or by a completely automatic system, if required.

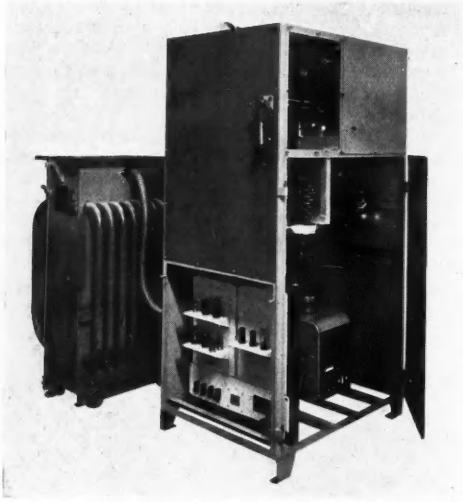

Fig. 66. Grid-controlled rectifier with adjustable output voltage, stabilized within ± ½% by a built-in electronic control unit. *(Courtesy of Nevelin Electric Co. Ltd.)*

Fig. 67 shows a rectifier cubicle made in the U.K. by the Electric Construction Co. Ltd. for their " Varispeed " drive, which normally comprises three pieces of equipment, i.e., the rectifier cubicle, the control equipment, and the d.c. drive motor. Typical figures for speed regulation with this equipment, when used with a mercury-arc-driven motor, are as follows:—At full speed (1000 rpm, output 400 hp), speed at no-load 1120 rpm; at ¼-speed setting (250 rpm, output 100 hp), speed at no-load 350 rpm.

(c) Motors Operated by Vacuum Valves or Gas-Filled Valves

Vacuum valves are capable of passing relatively small currents compared with gas-filled valves and are therefore only used to drive small motors. Gas-filled valves,

Fig. 67. Rectifier cubicle for a large " Varispeed " drive. *(Courtesy of Electric Construction Co. Ltd.)*

generally known as thyratrons, on the other hand, are extensively used in conjunction with motors up to about 75 hp. These valves, which can be filled with any one of a number of gases, e.g., mercury vapour, argon, etc., are similar to mercury-arc rectifiers, the main difference being that the thyratron has a solid, filament-heated cathode.

Electronic techniques can be exploited to the full to produce a speed-control device capable of first-class performance as regards speed range and regulation over the entire range, rapid speed changes being possible over speed ranges as high as 100:1. In low-power systems, power factor and efficiency are rarely a problem, poor though they may be over certain parts of the speed range.

Almost every manufacturer will have a different control circuit. Gas-filled valves are used in the armature circuits of motors, and gas-filled or vacuum valves in the low-current field circuits. This type of drive effectively achieves low speed by supplying power to the motor intermittently.

As with other types of drive, the greater the demanded speed range and the better the regulation, the larger, more costly, and more complex will be the equipment. The disadvantage of the required warm-up period, which may amount to several minutes, must always be borne in mind when considering electronic drives of this type. The main advantages may be summarized under the headings of high speed of response, small amount of control power, wide speed range, and good regulation.

In the " Airmec " electronic speed controller, manufactured in the U.K. by Crompton Parkinson Limited, armature supply is via two thyratrons, which are xenon-filled to reduce warming-up time to about one minute. These thyratrons provide a full-wave rectified supply which is reversible and continuously variable between 20 and 200 V d.c. at a maximum current of 5 A continuous rating. A choke and capacitor smooth the armature current, so that the approximate ripple voltage with maxi-

mum current is 15 V r.m.s. when the average voltage is about 100 V. For field supply, a full-wave metal rectifier is used, delivering 0·2 A maximum at 200 V d.c., unsmoothed. The complete unit, which is suitable for motor ratings of ½, ¾, or 1 hp, as required, with a standard top speed of 2850 rpm, consists of two units, i.e., the rectifier unit and the manual controller. The rectifier unit is shown in Fig. 68.

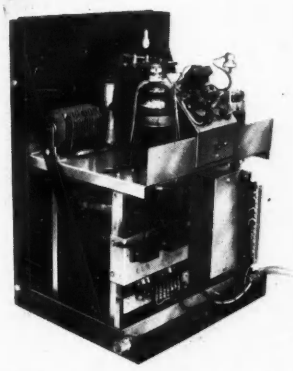

Fig. 68. View of interior of rectifier unit of the " Airmec " electronic speed controller.
(Courtesy of Crompton Parkinson Ltd.)

The " Heenatron " drive, manufactured in England by Heenan & Froude Ltd., comprises a d.c. shunt-wound motor rated up to 1 hp at maximum speeds of 2800, 1400, or 960 rpm. At the non-driving end, a permanent-magnet type of a.c. generator is built as an integral part of the machine, the voltage from it being directly proportional to speed. This generator may, however, be supplied as a separate self-contained unit for special applications or where non-standard motors are used. The motor is excited by an electronic rectifier unit operating on normal single-phase a.c. mains, supplying the direct current required for the motor. The unit employs mercury-vapour grid-controlled thyratrons. Governed by the generator, infinitely variable speeds down to 60 rpm are available, and set speeds are maintained within ±10 rpm, despite wide variations in load. An adjustable torque-limitation circuit protects the motor against overload, eliminating the need for a d.c. motor starter.

The components of a typical low-power system (1 to 3 hp) are illustrated in Fig. 69. Known as the " Emotrol " this system, made in the U.K. by The British Thomson-Houston Co. Ltd., is, however, available in a wide range of ratings, from 0·5 to 600 hp. All these units are essentially controlled rectifiers supplying the precise amount of d.c. armature power required to maintain the desired motor output. To cover the above power range as economically as possible, a variety of rectifier connections is used. Thus, the lower power ratings (up to 35 hp) use a biphase rectifier with two thyratrons, while, for ratings above 35 hp, six rectifier-type ignitrons are used. Where variation of the shunt-field excitation is required to obtain a very wide speed range or for other reasons, an auxiliary controlled-rectifier circuit is used.

In the U.S.A., a thyratron-fed d.c. motor drive, known as the " Thy-mo-trol " (Fig. 70), is made by General Electric, providing stepless speed control over a wide range, i.e., 5:1, 20:1, 50:1, or even 100:1. These packaged drives are available in many sizes, from 1/70 hp up to 75 hp. Other units of this type are made in the U.S.A. by the Louis Allis Co. (the " Select-a-Spede ", for ratings up to 15 hp) and by the Reliance Electric & Engineering Co., who use an electronic drive with printed

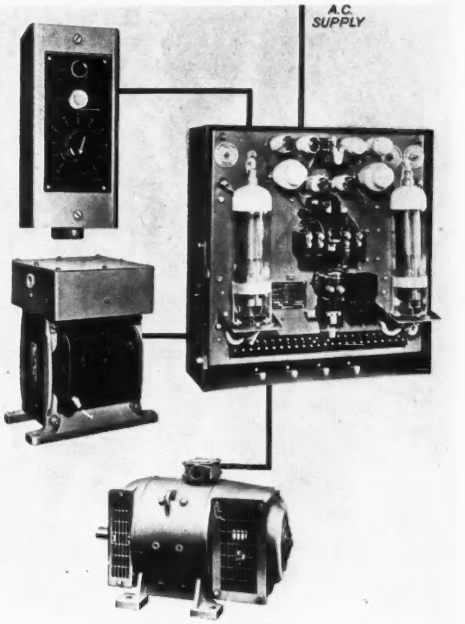

Fig. 69. Component units of typical low-horsepower " Emotrol " equipment.
(Courtesy of The British Thomson-Houston Co. Ltd.)

Fig. 70. The " Thy-mo-trol " packaged thyratron-fed motor-control drive.
(Courtesy of General Electric Company, U.S.A.)

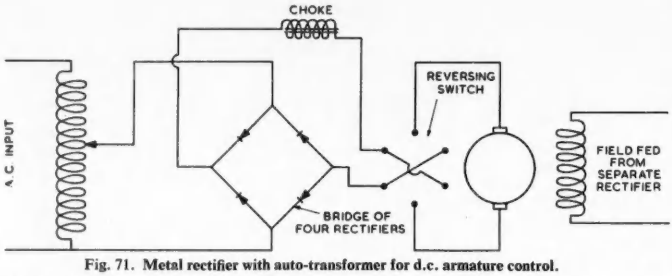

Fig. 71. Metal rectifier with auto-transformer for d.c. armature control.

circuits in the control panel. In Belgium, an electronically fed system (the "Motorel") is manufactured by A.C.E.C.

(d) Motors Operated by Metal Rectifiers

The advantage of the metal rectifier is its inherent robustness, since it consists simply of alternate layers of metal and alloy or metal and oxide. Provided that it is suitably cooled, it is extremely reliable and shock-resistant. Its output, however, cannot be controlled within the rectifier itself, as with mercury-arc or thyratron rectifiers, and it is therefore used in conjunction with an a.c. controller, either an auto-transformer, induction regulator, or magnetic amplifier. These controllers, like the rectifier, require virtually no maintenance and are rugged. For all but fractional horsepowers, magnetic amplifiers with a metal rectifier are more expensive than electronic drives, and their speed of response, whilst high, is a little slower than that of the electronic drive. Metal rectifiers are usually connected in "bridge" fashion, as shown in Fig. 71. Selenium rectifiers up to at least 125 kW output are available. As an indication of size, a 25-kW rectifier may measure approximately 31 × 25 × 79 in. and may weigh 1100 lb.

Fig. 72. "Magamp" ½-hp magnetic-amplifier-operated drive used for the control of a multi-core cable-making machine.
(*Courtesy of The English Electric Co. Ltd.*)

Recent developments in germanium and silicon rectifiers suggest that this type of rectifier may soon take its place in the list of available equipment of this type for d.c. motor control.

(e) Motors Operated by Magnetic Amplifiers

Although magnetic amplifiers are mainly used in control gear for Ward-Leonard systems, a number of variable-speed drives using motors operated purely by magnetic amplifiers are available for low-power applications. The transductor has a variable impedance, owing to its magnetic properties, and a control winding on the transductor core varies the impedance in the power circuit, thus effecting control of the power applied to the motor armature. The advantages of this type of drive include instantaneous speed of response and starting, as no warm-up period is required, compactness, good regulation, low cost, and wide speed range, e.g., 50:1.

In the "Magamp" ½-hp motor control unit, made in the U.K. by English Electric, the magnetic-amplifier system is used in conjunction with a servo-loop. All d.c. power is obtained by full-wave rectification of the a.c. supply by metal rectifiers mounted in the "Magamp" cubicle. Providing stepless speed variation of the motor over a 30:1 range, the "Magamp" system is flexible and can be supplied in any one of three basic categories, i.e., unidirectional speed control, bidirectional speed control, or tension control. A larger version, with a 3-hp rating and a 20:1 speed range, is also supplied by English Electric. An example of the "Magamp" ½-hp unit in an application involving the control of a multi-core cable-making machine is shown in Fig. 72.

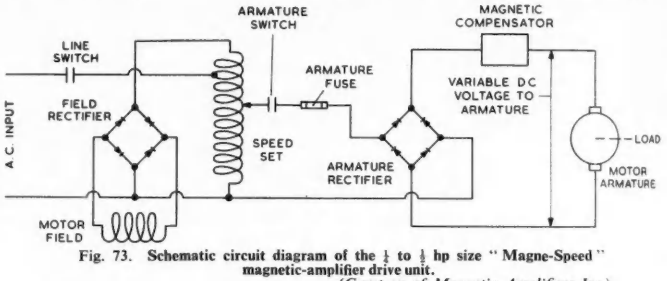

Fig. 73. Schematic circuit diagram of the ¼ to ½ hp size "Magne-Speed" magnetic-amplifier drive unit.
(*Courtesy of Magnetic Amplifiers Inc.*)

Fig. 74. Components of the ¼ to ½ hp size "Magne-Speed" magnetic-amplifier drive unit.
(*Courtesy of Magnetic Amplifiers Inc.*)

In the low-power range, speed-control systems incorporating magnetic amplifiers are becoming increasingly popular and are manufactured all over the world. Thus, for example, they are also made in the U.K. by Lancashire Dynamo Nevelin Ltd. (the " Varimag " unit), and in Germany by Siemens-Schuckert A.G. In the U.S.A., the " Magne-Speed " unit, made by Magnetic Amplifiers Inc., is available in three size ranges, i.e., 1/100 to 1/8 hp, $\frac{1}{4}$ to $\frac{1}{2}$ hp, and $\frac{3}{4}$ to $1\frac{1}{2}$ hp respectively. These units can be used with practically any standard d.c. motor within their ratings, and provision is made for dynamic braking and reversing, with local or remote control in all cases, as required. A schematic circuit diagram of the $\frac{1}{4}$ to $\frac{1}{2}$ hp size " Magne-Speed " drive is shown in Fig. 73, and an illustration of the components, giving an idea of their relative size, in Fig. 74.

Conclusion

In a survey of this type, it is quite impossible to describe more than a fraction of the total number of systems commercially produced, though every effort has been made to detail the characteristics of the major methods of electrical speed control. In this connection, it would appear that, although present developments in the U.S.A. suggest that the trend towards the use of a d.c. motor as the final drive is the right one, the author does not believe that this is necessarily the case. During the last few years, something of a revival in fundamental research into the theory of electric motors has been taking place and, as examples of fairly recent developments, the following may be mentioned :—

(a) The improvement in a.c. commutator motors, making commutation no more of a problem than it is in d.c. motors.
(b) The development of 3:1 pole-changing motors, thereby extending the application of squirrel-cage motors.
(c) The development of the new spherical brushless variable-speed motors, as described earlier.

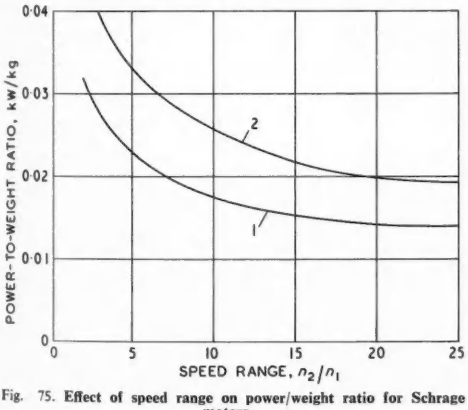

Fig. 75. **Effect of speed range on power/weight ratio for Schrage motors.**
(Courtesy of Brown, Boveri & Company Ltd.)

Furthermore, it can be argued that any step towards producing motors with no rubbing contacts should be the right one, as this removes considerable maintenance trouble and results in a more robust machine. Also, it should be noted that, of the three developments mentioned above, two are self-contained machines involving virtually no auxiliary equipment.

From the foregoing discussion one feature emerges above all others, i.e., that there is always a penalty to be paid for variable speed. Whether this penalty is the actual capital cost of the equipment, or the running and maintenance costs, or such factors as weight, size, efficiency of regulation, etc., or a combination of any of these factors, no variable drive is immune from this drawback. It is not surprising, therefore, that sometimes the problem has been tackled by designing a project to suit a constant-speed motor, rather than accepting the penalties incurred by variable speed. In some cases this is undoubtedly the best solution, but there are, nevertheless, many problems where these penalties must be paid, and it is here that the engineer must decide the best way in which this can be done. The few specific examples that follow serve to illustrate a few general rules which are concerned with demand and price.

Fig. 75, compiled by Brown Boveri in connection with Schrage motors, shows the effect of speed range on power/weight ratio for a motor rated at 4 kW at a top speed of 1900 rpm (curve (1)) and another motor rated at 9 kW at 2100 rpm (curve (2)). From curve (1), it can be seen, for instance, that, if the speed range is increased

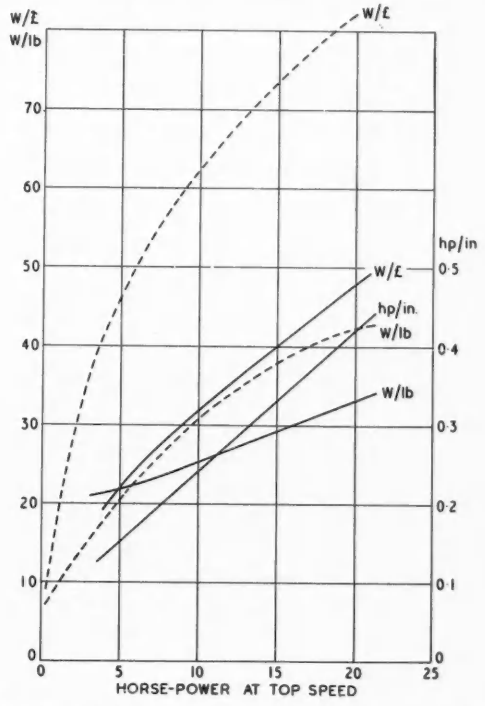

Fig. 76. **Variation in overall length, weight, and cost of motors for different power outputs.**
Full lines : Schrage motors, with a 4 : 1 speed range.
Dotted lines : d.c. motors.

TABLE III : COMPARISON OF VARIABLE-SPEED DRIVES GIVING 7/14 HP AT 375/750 RPM

Type of machine	Efficiency [%]			Power factor			Power/weight ratio [hp/lb]	Relative cost [%]
	High-speed setting	Middle-speed setting	Low-speed setting	High-speed setting	Middle-speed setting	Low-speed setting		
Schrage motor ..	79	78	67	0·99	0·77	0·65	0·0088	380
Ward-Leonard set ..	65	63	60	—	—	—	0·0080	400
A.C. commutator motor	76	78	77	0·90	0·75	0·65	0·0071	450
Spherical motor ..	61	68	75	0·84*	0·83*	0·81*	0·0105	340†
Squirrel-cage motor (14 hp at 500 rpm) ..	—	85	—	—	0·71	—	0·0180	100

* Taken from theoretical considerations and probably optimistic. †Including 80% contingencies.

from about 2·5:1 to 15:1, the weight of the motor is doubled. First cost and size are, of course, inevitably increased when an increase in weight is indicated. Fig. 76 shows a relationship between power and overall length, weight, and cost for Schrage motors of varying power with a 4:1 speed range. The dotted lines in Fig. 76 show the relationship between power and weight and cost for d.c. machines. For Ward-Leonard sets, two d.c. machines are required, plus the prime mover, so that the figures given for watts/lb and watts/£ should be divided by about 2·5 when considering a Ward-Leonard set.

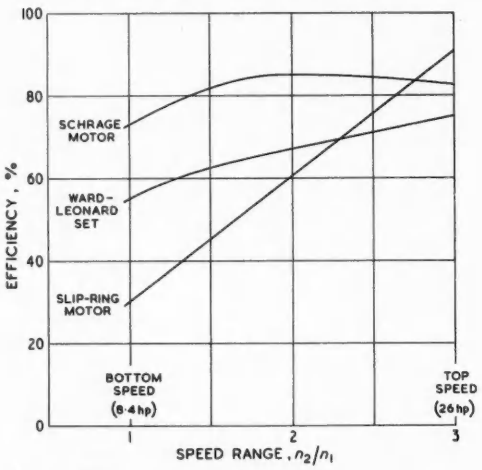

Fig. 77. Comparison of efficiencies of a slip-ring motor, a Schrage motor, and a Ward-Leonard set over a 3:1 speed range.

Fig. 77 shows the comparative efficiency of slip-ring, Schrage, and Ward-Leonard drives over a 3:1 speed range. If the speed range chosen were higher, the efficiency of the slip-ring motor would be much lower, whilst the Ward-Leonard would probably gain a little on the Schrage.

Although the new spherical brushless variable-speed motor is not yet being produced for sale commercially, estimates of its cost, power/weight ratio, and efficiency have been made for comparison with other types of drive. Table III shows that the new motor has advantages other than its robustness and brushless features, and also emphasizes the superiority of a conventional, constant-speed squirrel-cage motor both from cost and size considerations.

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Flow and Fracture

By E. R. PARKER.* (From *Metal Progress, U.S.A.*, Vol. 72, No. 5, November 1957, pp. 65–69.)

MANY of the advances made in metallurgy during the past 150 years have been associated with chemical technology. To-day, however, the position is different, inasmuch as metallurgy has reached the point where advancement depends on a knowledge of solid-state physics. Solid-state science will unquestionably play a major role in the discovery or invention of new materials, and will also lead to an improved understanding of the behaviour of existing materials, thereby extending their practical applications.

The important lesson to be learned from the list of metals which have become important in the decade following World War II, such as germanium, high-purity silicon, titanium, zirconium, uranium, and plutonium, is that a host of new materials, many of them non-metallic, is now appearing on the scene. There are, however, too many combinations of elements possible for investigations to be made by trial-and-error methods. Even though actual test results will provide the background information necessary to select the new materials, intelligent application of basic principles is the only feasible means of attacking the problems ahead.

Bearing in mind the above, this paper reviews the concepts of flow and fracture which have slowly developed during the past twenty years, and shows how these concepts can lead to the development of new or improved materials, as well as providing a better understanding of the behaviour of those now in commercial use.

DISLOCATIONS

Prior to the conception of the dislocation theory, slip was known to take place on certain crystal planes and always in the direction of closest atomic packing. Theoretical calculations indicated that the yield strength of metallic crystals should be of the order of 10% of the shear modulus. However, real crystals were known to yield at stresses of only a few pounds per square inch. This observed weakness could not be explained if the crystals were really perfect, as assumed. Prior to 1930, there had been some speculation that crystals usually were imperfect, and there was rather convincing X-ray evidence that this was the case. If crystals actually contained flaws, then their weakness might be explained on the basis of the stress concentrations existing around the defects. It was this sort of logic that led to the dislocation theory in 1934 by Taylor and Orowan. Taylor even developed a mathematical theory based on interaction of the stress fields surrounding dislocations to explain how and why work-hardening occurred.

The dislocation theory was elaborated slowly during the first decade of its existence. It was generally accepted as a theoretically satisfactory tool, but there was no direct experimental evidence to confirm its validity. To-day, experimental techniques have improved at an almost unbelievable rate and the modern electron microscope can watch individual dislocations move within metal crystals. Other experiments with transparent ionic crystals have further confirmed the existence of dislocations and the theoretical predictions of their behaviour.

The newly developed experimental techniques and refined predictions of the theory have led to an understanding of the causes of such phenomena as strain-hardening, creep, yield point, solution-hardening, precipitation-hardening, and grain size effects. Not quite matured, but developing rapidly, is an understanding of fracture phenomena, such as cleavage and ductile fracture, fatigue, intergranular cracking, and stress-corrosion cracking.

STRAIN-HARDENING

It now appears that the answer to the question regarding what occurs in a metal to make it harder and stronger has at last been found. Experiments with single metal crystals strained in simple shear have shown that dislocations moving through a crystal lattice under the action of a shear stress are occasionally retarded by barriers encountered in their progress. Various kinds of imperfections or discontinuities can act as barriers, e.g., other dislocations, grain or sub-boundaries, and particles of a second phase.

Experiments have shown that, when slip occurs on only one slip plane and in a single direction, the resulting strain-hardening is due entirely to entanglement of dislocations at barriers. Dislocations tend to loop around these barriers, but the trapped dislocations are retarded, and the stress must be increased before flow can continue. Technically speaking, the trapped dislocations produce a " back stress " in opposition to the applied stress, and the applied stress must increase if flow is to continue. One important cause of work-hardening is this back stress.

There seems to be only one other major contribution to work-hardening, i.e., that due to the combination of two dislocations originating on different slip systems. When two such dislocations meet, they combine to form a new dislocation having a slip vector in a direction different from that of either of the reacting dislocations and often in a direction where the lattice is unreceptive to slip. Combined dislocations form lattice discontinuities which moving dislocations can penetrate only with extreme difficulty. Thus, when slip occurs on more than one slip system, new barriers to moving dislocations are continuously being generated during the flow process, and this phenomenon contributes to strain-hardening.

When a metal is deformed at room temperature and then reheated to successively higher temperatures, several changes occur to relieve the acquired state of strain. Dislocation loops that have expanded outward from their source and have been held up by barriers tend to collapse, gradually becoming smaller and finally disappearing back

* This article is based on a digest of the Campbell Memorial Lecture presented by the author before the A.S.M. in November 1957.

into the source whence they came. This process happens rather easily and quickly. It has little effect on the hardness or strength of the metal, but reduces internal stresses substantially and improves electrical conductivity.

A second process is the annihilation of dislocations by the combination of pairs of opposite sign. This process generally requires the movement of the dislocations in the direction perpendicular to the slip plane—a process known as "climb", which involves the condensation of vacancies or extra atoms on the dislocation line. The climb process is diffusion-controlled, and hence the rate of climb versus temperature follows an exponential relationship.

A third phenomenon contributing to recovery is the formation of a substructure due to the collection of like dislocations in boundary walls, usually forming on surfaces perpendicular to the slip plane. As predicted by theory, such an array constitutes a low-energy configuration of dislocations. Climb is also involved in subboundary formation, so that this formation is also diffusion-controlled.

Creep

During the past five years it has become increasingly clear from theory and experiment that creep is controlled by dislocation climb, which in turn is controlled by self-diffusion. The activation energies found for the creep of almost all metals coincide with those for self-diffusion. Furthermore, simple single-crystal experiments have shown that the dislocations stopped by barriers at low temperatures are only temporarily retarded at creep temperatures. X-ray evidence has shown clearly that dislocation climb and substructure formation are associated with high-temperature creep. Thus, in recent years experiments have shown that the rate-controlling process is dislocation climb, and climb is necessary to permit dislocations to move past the barriers that stopped them.

Most of the theories formulated to date have been based on the assumption that the source had to be thermally activated or that the movement through the lattice required thermal activation. Since the rate-controlling step is the escape of dislocations at trapping barriers, any theory based on these assumptions cannot be correct. Only within the past two years has a reasonable theory been formulated with the assumption that climb is the rate-limiting step.

The shape of the creep curve has recently been explained, and it is now possible to control the curve shape, changing it from its normal concave downward configuration to a straight line, or even reversing its direction of curvature. This can be done with simple procedures which produce subtle changes in the structure of the material.

Solution-Hardening

Exactly what happens within an alloy to make it harder and stronger than the base metal is still a matter for speculation, but it seems rather clear now that solution-hardening is due to the interaction of solute atoms with dislocations. Just how and why these interactions occur is the problem. Experiments with steel have shown that the yield point is due to dissolved carbon or nitrogen concentrated in dislocation walls or grain boundaries which stop the movement of dislocations. The shorter the distance between the pinned barriers, the higher is the yield strength.

The mechanism of substitutional solution-hardening has been more obscure. A number of theories have been advanced but none has been verified experimentally. Recent experiments with alloy single crystals indicate that the hardening process is similar to that for interstitial alloys, i.e., it is due to the interaction of solute atoms with substructure boundaries. The evidence is clear that solution-hardening is caused neither by the pinning or deactivation of the source nor by retardation of dislocations as they move through the relatively perfect portions of the lattice.

Solution-hardening has been shown to be structure-sensitive, and so it is now clear that this phenomenon cannot properly be described by a simple general mathematical law.

Hardening in Two-Phase Systems

The cause of hardening in two-phase systems has not been elucidated to any significant extent, principally because solution-hardening has been so puzzling. Plastic flow must still occur in a ductile matrix in which are dispersed hard brittle particles. Unless the flow and strain-hardening processes occurring in a saturated solid solution (the matrix) could be clearly understood, it would obviously be impossible to understand how such a substance could flow when it contained a dispersed second phase. Now that an understanding of the mechanism of solution-hardening seems to be at hand, the problem of plastic flow in a two-phase system can be attacked with some assurance of success. This, however, has not been done as yet.

Fracture

There is a number of different kinds of fracture, including cleavage, shear, fatigue, intergranular, and stress-corrosion fractures. Fracture is known to be a two-stage process involving nucleation of a crack and growth of a crack. Theories describing growth processes are relatively simple to devise; indeed, a number has already been formulated. It is the crack nucleation that presents the real problem at present.

Recent work on the origin of fracture nuclei in fatigue has been illuminating. Experiments have shown that, at least with some metals, cracks develop on the surface, because flow occurs successively on two slip planes intersecting one another near a free surface. Periodic removal of the surface layers prolongs fatigue life indefinitely. In other experiments, single crystals of zinc were subjected to reversed cycles of simple shear; in a room-temperature test, with a strain amplitude of 1%, the crystal was unharmed, even after 3×10^6 cycles.

Some of the conditions necessary to avoid or to cause fatigue have been disclosed, and it seems that an understanding of the basic processes leading to fatigue will soon be forthcoming. However, with regard to ductile shear-type fractures and stress-corrosion cracking, the theoretical picture is still vague and unsatisfactory. Both of these processes involve nucleation and growth of cracks, but at present there is no acceptable picture of how cracks get started or how they grow.

Non-Metallic Crystals

From the accumulated knowledge of flow and fracture processes, it seemed reasonable to conclude that certain non-metallic materials, particularly cubic ionic crystals, should exhibit plastic properties like those normally associated with metals. Earlier work on sodium chloride and on silver chloride strongly supported this conclusion. A rather large fundamental programme has recently been

(*Concluded on page 576*)

Stress Corrosion in Austenitic Steel by Nitrates

By O. Lissner. (From *ASEA Journal*, Vol. 30, No. 5, 1957, pp. 85–91, 13 illustrations.)

In this article, an account is given of the investigations carried out as a result of the fracture of an end bell from a turbo-generator set. Proof is given that this fracture was the result of stress corrosion caused by the presence of nitrates, an interesting and surprising fact which shows that the phenomenon is quite unlike all previously known end-bell faults. Questions concerning the choice of material and precautionary measures are also discussed.

In 1955, an explosion occurred in the exciter end of one of the three turbo-generator sets at the Vaal Power Station in South Africa. The set consisted of a 33-MW steam turbine of the STAL double-rotation radial-flow type, coupled to two ASEA turbo-type generators, each with an output of 20 MVA at 1500 rpm. At the time of the accident, the set had been in service for a total period of about 71,000 hr, and, in addition, had undergone 236 starting operations and 113 overspeed tests.

Inspection revealed that a certain amount of damage had been caused in the ventilator drum in the basement and that the rotor-coil ends, stator-coil ends, and certain parts of the supporting structure were completely destroyed. The inner housing, constructed of silumin, was broken into small pieces, but the outer cast-iron housing was able to contain all the damaged parts. The end bell (retaining ring), which remained hanging on the generator shaft, proved to be cracked, the fracture running right through two ventilating holes, as shown in Fig. 1. It was evident that the fracture in the end bell was the primary cause of the breakdown, and the investigation was limited, therefore, to a study of the origin of the fracture.

After the fractured end bell had been removed and cleaned, it was noted that the surfaces of the fracture were separated about 60 cm from one another, and that the fracture appeared to be of a brittle nature. In addition, a large number of cracks could be observed on both the outside and inside of the end bell. Cracks could be seen at all the ventilating holes adjacent to the outer ring end, while a few were also present at several other holes. Furthermore, there was a network of numerous fine, but very extensive, cracks on the smooth surfaces of both the inside and outside of the end bell. These latter cracks branched out in various directions, but all showed a general tendency to spread out axially and had no connection with the ventilating holes. Examination of the remaining three end bells of the damaged set revealed that they also had a large number of cracks.

Choice of Materials for End Bells

Austenitic non-magnetic steels have been used for several decades in Europe for the manufacture of end bells for turbo-type generators. Nowadays, of course, only cold-expansion methods of manufacture are employed, i.e., conical or expanding tools are used and the temperature is not allowed to rise above 400°C after the roughly forged rings have been annealed. However, end bells were originally constructed by the hot-cold forging process, i.e., they were forged with the aid of a mandrel at an elevated temperature of about 600°C, and this method was still in use when the Vaal end bells were manufactured. With this method, which has now been discontinued, heating up to, and forging from, about 620°C leads to considerable carbide precipitations at the grain boundary of the austenitic material used (Fig. 2). This can cause a marked reduction in the ductility of the material. In the case of the Vaal end bells, relatively low ductility was obtained. If, in addition, there are certain areas of high stress concentration, e.g., around the ventilating holes in end bells, there is a danger of brittle fracture.

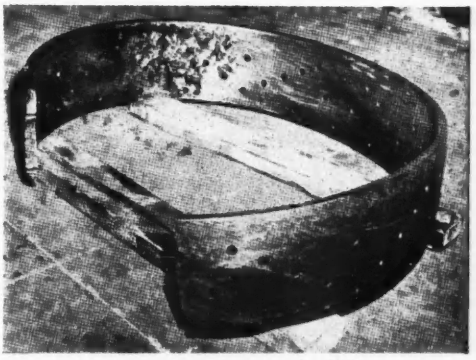

Fig. 1. View of the fractured end bell.

Investigations of the Cracks in the End Bells

In order to find out the cause of the fracture and the formation of cracks in the end bells, a study of the cracks, their origin, depth, appearance, nature, and especially their development in the material was carried out. A record was therefore made of all the cracks on the four end bells from the set which failed.

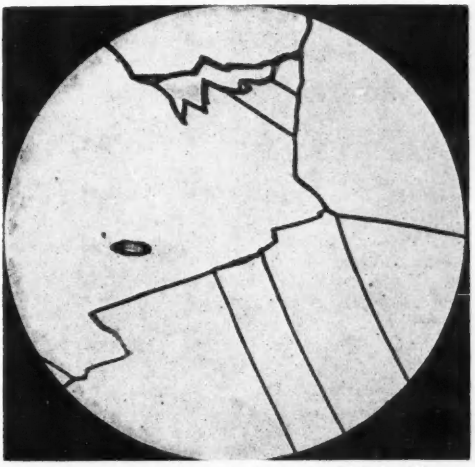

Fig. 2. Micro-structure of the fractured end bell. (×625)

On the two end bells of the generator which broke down, detailed examination showed not only large and partly open cracks extending from the edges of the ventilating holes, but also an extremely large number of fine cracks, which often developed into continuous networks. These networks formed a ring on the outside of the end

bells, adjacent to the chamfered edge, while those on the inside were mainly located in the spaces between the coil ends. The coil ends were protected with U-sections of aluminium, which surrounded the turns and were in direct contact with the end bells. The two end bells from the other generator in the same set had basically the same appearance, even if there were slightly fewer cracks. It was not possible, however, to detect any networks of cracks on the inside of these end bells in the spaces between the coils.

Similar observations have been made by other investigators, especially the manufacturers of end bells. Thus, the same type of crack formation has been noted on several older end bells in the course of routine inspection of generators. In these cases, it has been possible to avoid breakdown by replacing the end bells. Examinations of such end bells, which have been carried out in Austria, Germany, and Great Britain, have all shown that stress corrosion has been the cause of these cracks. Indeed, it has even been reported that stress corrosion has been noticed on end bells which have merely been kept in store for a certain period in a humid atmosphere. When these end bells were to be used, crack formations were observed, which, as is the case with all other examples of stress corrosion in end bells known up to now, were caused by the presence of chlorides, in conjunction with humidity and high residual stresses.

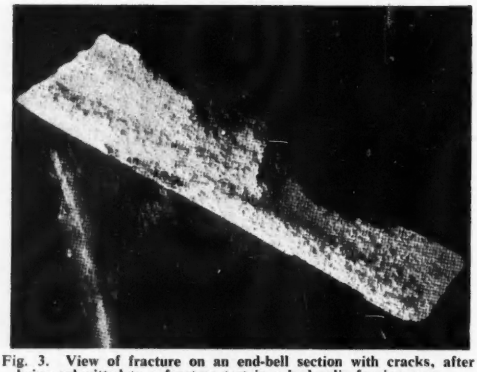

Fig. 3. View of fracture on an end-bell section with cracks, after being submitted to a fracture test in a hydraulic forging press.

Several samples, about 500 mm long and 200 mm wide, were cut from the end bell which had failed. These were placed in a hydraulic forging press and bent until they burst. Fine cracks opened out in many places, and the fractures developed from one, or more, of the largest cracks. A yellowish-brown colouring was then noticed in the opened cracks, as well as on the surface of the fracture. The coloured surface gave an indication of the depth of the cracks, which amounted to from 10 to 12 mm. One such fracture from one of the tests is shown in Fig. 3.

The supposition that the formation of cracks was caused by stress corrosion was now considerably strengthened. This hypothesis could not, however, be directly proved by chemical analyses.

A microscopic examination carried out later showed that the cracks, in every case, progressed in a purely intergranular manner, i.e., limited to the grain boundaries. Such a purely intergranular development of a crack in the fractured end bell is shown in Fig. 4.

Chlorides, however, only give rise to cracks with a purely transgranular progress, i.e., right across the grains.

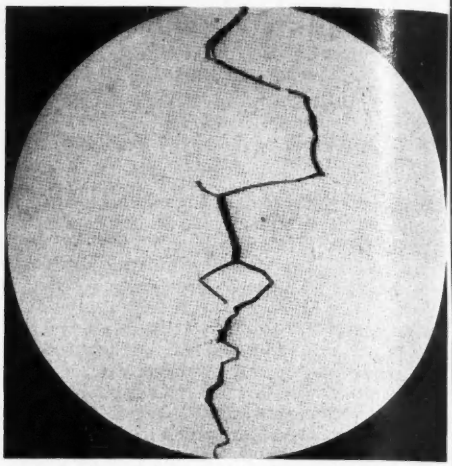

Fig. 4. Development (intergranular) of a crack in the fractured end bell. (×90)

Several tests carried out on the material available confirmed this fact. In this connection, Fig. 5 is an example of stress-corrosion cracks caused by chlorides in a sample taken from the fractured end bell, using a tuning-fork test in a solution of boiling 42% HgCl.

As a corrosive agent which causes intergranular stress corrosion in this type of steel was hitherto unknown, a number of experiments were carried out with different corrosive media, as described later.

Brittle-Fracture and Fatigue Tests

Brittle-fracture tests, which were performed on notched round bars, gave no indication of any great tendency in the material to brittle fracture, and it was therefore concluded that the failure could not have been caused by this phenomenon. The large number of cracks in the four end bells implied that it was a question of a slowly developing growth of cracks, and that such a phenomenon could not be associated with brittle fracture.

Fatigue tests were carried out on fairly large segments

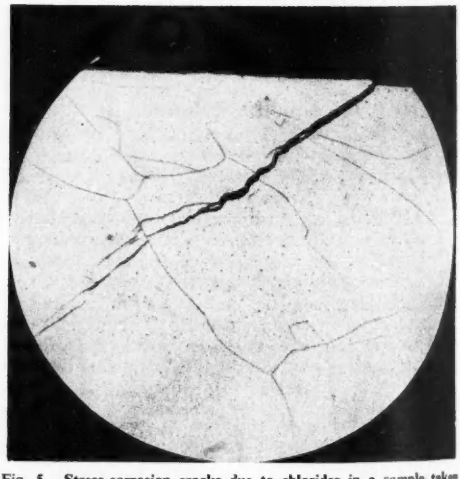

Fig. 5. Stress-corrosion cracks due to chlorides in a sample taken from the fractured end bell. (×225)

cut from the end bells. These samples were subjected to pulsating bending stresses of up to about 31 tsi. Not a single case of fatigue fracture was obtained after 20,000 such cycles. Moreover, similar tests on smaller bars did not yield especially low fatigue-resistance values.

Stress-Corrosion Tests

The theory already mentioned that stress corrosion was the origin of the fracture of the end bell resulted in a rather extensive investigation with the object of discovering the specific corrosive agent which leads to intergranular corrosion in this type of austenitic steel.

There is only a limited number of corrosive media available for testing austenitic steel when investigating stress corrosion. Four reagents were used, i.e., (1) a slightly acid solution of 2% $FeCl_3$; (2) a solution of 3% NaCl at 80°C ; (3) a solution of 60% $CaCl_2$ and 0·1% HgCl, which is slightly acid and has an oxidizing action, owing to the HgCl ; and (4) a solution of 0·1 *N* HCl and 1% $FeCl_3$, which especially attacks martensite. However, none of these reagents reproduced the typical intergranular stress corrosion experienced with the Vaal end bells.

Samples from the end bells were finally tested in a solution of calcium-ammonium nitrate. A solution with 36% calcium nitrate and 3% ammonium nitrate having a boiling point of 105°C was employed in these tests. Striking results were obtained, since all the known steels used for end bells showed crack formations after a very short time, compared with ordinary carbon steel. The development of the stress-corrosion cracks was purely intergranular, as can be seen in Fig. 6, in which a bending stress of 19 tsi produced cracks in a test sample from the fractured end bell in 44 hr.

A manganese-chromium steel also developed intergranular cracks. Bending stresses of about 19 and 29 tsi within the range of the operating stresses brought about stress-corrosion fractures within 50 hr. At 41 tsi, the life was reduced to about 2 hr. Finally, it was possible to prove that stress corrosion could take place even in very dilute solutions of calcium-ammonium nitrate.

The Origin of Nitrate Corrosion

The formation of nitrates in high-voltage generators could indeed be attributed to corona phenomena and the subsequent formation of ozone and the oxidation of nitrogen. Chemical analyses, however, on the end bells from the set which failed did not give any indication of nitrates. Since the end bells were cleaned and greased before they were dispatched from South Africa and then later degreased, this was nevertheless not a valid proof to the contrary.

Finally, it was decided to carry out an examination of the deposits formed at the coldest spot in the ventilating system of the generator, i.e., on the lower cooling pipes in the air-cooler.

There were no difficulties in carrying out this examination on several Swedish generators, but the results were negative. Samples of the deposits from the Vaal machines were then sent to Sweden and large amounts of nitrates were discovered. Chemical analyses gave positive results, and an additional check by means of X-ray diffraction gave added confirmation to the results already obtained.

The reason for the fracture was now clear, but there was still no explanation as to why this type of stress corrosion had arisen in only one of the Vaal sets. In the case of more recently built generators, the risk could be regarded as being considerably less, the latter being provided with more effective corona protection, which radically reduces the corona effect and the subsequent formation of nitrates. The explanation was finally found in the fact that the nitrate deposits proved to be much more extensive in the set which broke down than in the other sets. The reason why the nitrate deposits were much more pronounced in the one Vaal set than in the other two, and in the Vaal Power Station as a whole, compared with other power stations, could not, however, be explained.

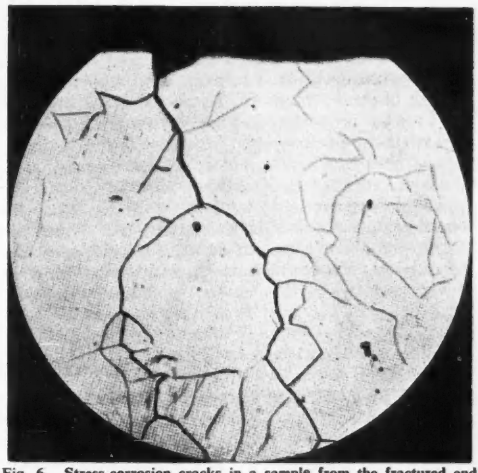

Fig. 6. Stress-corrosion cracks in a sample from the fractured end bell, tested in a solution of calcium-ammonium nitrate. (×50)

Precautions against Stress Corrosion

It is a very complicated problem to eliminate the risk of stress corrosion caused by nitrates on all the known materials used for end bells, as long as the nitrates are formed in relatively large quantities. The pronounced development of nitrates in the Vaal Power Station is, however, unique. Various Swedish power stations, where the ozone concentration in the cooling air is relatively high, have also been investigated. No traces of nitrates were found on the air-coolers. One measure is, of course, to provide effective corona protection. The corona phenomenon does not give rise, however, to any aggressive products in hydrogen-cooled machines.

The risk of stress corrosion can be reduced if the yield point of the material is lowered. Ventilating holes increase the mean stress in the end bell and, in addition, points of excessive residual stress are liable to occur around the holes. The temperature rise for the Vaal rotor was so low that new end bells without any holes could be used.

It should nevertheless be emphasized that the elimination of the ventilating holes is primarily intended to reduce the risk of brittle fracture. The cold-expanded, non-magnetic end-bell material used for generators with a moderate peripheral speed can be processed in such a way that an extremely ductile and even quality is obtained. In this way, the local stress concentrations around the ventilating holes are equalized, owing to plastic deformation. When the peripheral speed of the rotor is very high, the degree of cold working of the end-bell material must be increased. As a result, the ductility of the material is reduced to such an extent that it is preferable to use a system where ventilating holes are not required. This will also delay slightly the formation

of cracks, if the material is subjected to stress corrosion.

Stress-relieving annealing has been introduced, and this reduces the internal stresses in the material. Finally, the application of cathodic protection, e.g., a coating of varnish with a high zinc content, can greatly diminish the risk of stress corrosion. The inside of the new Vaal end bells has been treated in this manner, since it is easy to apply a durable coating. Treatment of the outside of the end bells is, however, a more difficult problem. This has not been done in the case of the Vaal generators ; instead, a regular inspection is proposed. Since the investigations of the Vaal generators have shown that the formation and growth of cracks have developed very slowly, it is possible to discover by carrying out an inspection in good time any signs of stress corrosion and, if necessary, replace any end bells of doubtful quality.

The question now arises about the possibility of developing new end-bell materials which are not sensitive to stress corrosion, whether caused by chlorides or nitrates. It is the author's opinion that this goal can be achieved if stainless austenitic steel, with a chromium content of more than 12% and with a considerably lower supersaturation with carbon (i.e., less than 0·2% C) is used. Satisfactory results have already been obtained with a steel containing 0·2% C, 12% Cr, 12% Ni, and 6% Mn. A nickel-free steel containing 0·08–0·20% C, 12% Cr, and 20–24% Mn also appears to be promising.

U. S. A.

Thermoplastic Materials for Pipes

By P. M. Elliott. (From *Corrosion*, Vol. 13, No. 10, October 1957, pp. 49–55, 8 illustrations.)

Plastics, with their low specific gravity, generally good chemical resistance, good electrical properties, and general ease of handling, are obvious raw materials for piping, and it is not surprising that during the last decade ever-increasing amounts of plastic materials have been used for pipe production. The currently important thermoplastics for this purpose are polyethylene, acrylonitrile copolymer-blend compounds, cellulose acetate butyrate, polyvinyl chloride, and polyvinylidene chloride. It is expected that large amounts of polyethylene will continue to be used, but the special properties of other materials, notably polyvinyl chloride and acrylonitrile copolymer-blend materials, are expected to increase their share of the total market.

General Properties of Plastic Pipes

As a class, plastic materials have certain general advantages relative to the metals commonly used for pipe production. Plastics have considerably lower density than even aluminium ; hence, plastic pipe is light in weight, which makes it easy to handle, easy to ship, and easy to store. The generally good electrical properties of plastic materials eliminate the electrolytic effects which are proving so troublesome in many pipe installations. Even metals that are not attacked by direct corrosive action may be damaged by electrolysis. Plastics in general are not subject to " corrosion ". Resistance to acids, alkalis, salts, and oxidizing media vary widely from material to material, but many of the plastic pipe materials have good general chemical resistance. This is of importance from the consideration not only of the materials being carried within the pipe but also of the external surroundings.

Plastics, in general, have little or no tendency to introduce contamination into materials being transported. In metal pipes, rates of solution which may not be serious from the point of pipe corrosion may still be detrimental because of the catalytic effects of many metal ions, even at low concentrations.

From the standpoint of long-term economy, plastics frequently have an advantage over metal pipe. Even in cases where the initial cost per foot of the plastic pipe may be higher than for some other types of pipe, the ease of installation and long life expectancy of plastic pipe add up to a more economical installation than a corresponding metal piping system.

It should be remembered, however, that plastic piping has certain definite limitations. The thermoplastic pipe materials in general have considerably lower tensile strength than the metals. As a result, plastic piping is limited to low- or moderate-pressure installations.

The fact that thermoplastics soften when heated means that they lose strength as temperature is raised, so that the upper temperature limit of serviceability is relatively low. Even the best present thermoplastic pipes usually are not recommended for use at temperatures above 170°F in applications where there is much, if any, internal pressure. A few experimental installations have been made at temperatures as high as perhaps 220°F, but this is certainly an upper limit for current pipe materials.

As mentioned above, the chemical resistance of each material is an inherent characteristic. The choice of pipe material will be dictated by the chemicals with which it is to come into contact and must be the subject of careful study. In many cases, the material manufacturer and the pipe producer will not have definite information on the resistance of a given pipe material to a specific set of corrosive conditions. It then becomes necessary for the purchaser to make a test installation or to take a calculated risk on the basis of the information available.

The moderate stiffness of thermoplastic pipe materials, plus the fact that they are subject to flow when stressed (particularly if the temperature is high), means that extra care must be taken in the support of above-ground installations. Another factor which has frequently been overlooked and which has caused failure in some pipe installations is the relatively high coefficient of thermal expansion of plastic materials. Most thermoplastics have coefficients of thermal expansion at least five times that of steel and, for some materials, the difference may be as high as fifteen times.

Joining of Plastic Pipe

The lack of availability of suitable fittings and valves for use with plastic pipe has been and continues to be a problem in the growth of many applications. In the early application of plastics in the piping field in the U.S.A., much flexible material was used. The pipe was made available in long coiled lengths which, among other things, decreased the number of fittings required in any given installation. Metal insert fittings and metal clamps were used to fasten together the individual lengths of pipe. As suitable injection-moulding compounds became available, plastic fittings were developed, and most

flexible pipe is now joined with plastic insert fittings. Metal clamping bands are still commonly used.

For the joining of rigid pipes, several methods have been employed. Thus, for a number of the heavier-wall pipes, standard threaded fitments of type II PVC and polyvinylidene chloride have been used successfully. It has been found that ordinary pipe-threading equipment, if used with reasonable care, will form suitable threads on these pipes. Another method of joining rigid pipes is by solvent or cement welding. This method is particularly suitable for thinner-wall pipes.

Temperature Effects

Since the materials under discussion are all thermoplastic and therefore soften with increasing temperature, it is obvious that temperature must have a significant influence on strength characteristics.

Table I: Upper Temperature Limits

Material	Recommended Range [°F]	Generally Used Upper Limit [°F]
Polyethylene	105–130	120
Acrylonitrile copolymer blends	150–180	170
Polyvinyl chloride, type I	130–170	145
Polyvinyl chloride, type II	130–170	140
Cellulose acetate butyrate	140–160	140
Polyvinylidene chloride	100–170	—

On the basis of the figures obtained in various tests, coupled with " case histories " of actual installations, the upper limits for the use of various pipes have been published on various occasions. Recommended upper temperature limits are listed in Table I for various materials.

Long-Term Effects

It has long been known that plastic pipe materials, like many others, cannot sustain for long periods the stress levels determined in short-time tensile tests. At stresses considerably below the tensile-strength values, the materials are subject to creep or may even fail by complete rupture.

As an example of the significance of long-term effective tensile-strength figures, a series of tests on acrylonitrile copolymer-blend materials has shown that, if pressure in the pipe is increased rapidly enough to cause bursting in about 30 sec, the fibre stress at bursting is 5400 psi. If, however, the pressure increase is less rapid, so that the duration of the test is 5 min, the fibre stress at bursting is about 4900 psi. It is obvious, then, that extension of such a test to a point where bursting would take place in, say, ten years would give a figure considerably below this level.

As a result of tests carried out by the author on pipes made of acrylonitrile copolymer blends, stressed at various levels and held under pressure to see how long they would last, it is predicted that, at a fibre stress of 1550 psi, such a pipe would have an average life of one year, while, at a fibre stress of 1330 psi, the minimum average life should be ten years. On the basis of such data, together with available field experience, the long-term effective tensile strength of the acrylonitrile copolymer-blend material now used in the production of pipe has been set at 1220 psi at 73°F.

Similar results have been obtained by various other investigators, but it may be said that, because of differences in temperature and even in the materials tested, it is impossible at the present time to correlate the various figures obtained with the data gathered.

Applications of Plastic Pipe

In considering the applications of the various thermoplastics in the field of plastic piping, it is necessary to differentiate between the different types, taking into account their general physical properties and chemical-resistance characteristics. The special features of the various materials also will be considered.

Polyethylene :—

Polyethlyene, because of its lower modulus, is normally classified separately from the other thermoplastic pipe materials, since it gives a " flexible " pipe rather than a truly rigid one. Currently, polyethylene is used in the largest volume of any plastic pipe material. It has the lowest specific gravity and the lowest cost per pound, and its flexible nature and toughness over a wide temperature range permit exposure to freezing without damage. Polyethylene in sizes up to 2 in. is at present supplied in long coil lengths, thus permitting economy in installation of long lines through reduction in the number of joints required and the time necessary for laying the pipe. The relatively low tensile strength and low softening point of polyethylene limit its use to moderate pressures and temperatures, and its softness makes it susceptible to cutting damage in handling or in burial. Polyethylene has excellent corrosion resistance to practically all acids, alkalis, and salt solutions, except strong oxidizing media. It is, however, susceptible to a phenomenon of stress cracking which is accentuated by certain polyoxyethylene-type organic materials.

The main applications of polyethylene are in handling cold water. It is used in a large number of jet-well installations and in many rural domestic and farm water systems. Lawn sprinkler systems and large irrigation systems are using large amounts of polyethylene, and it has found favour in handling corrosive waters in applications such as mine drainage. Its good low-temperature properties have permitted its use as cooling coils in skating rinks, and it also has been used as the heating coils in radiant-heating installations, in which it gains support by being buried in concrete.

Acrylonitrile Copolymer Blends :—

The acrylonitrile copolymer blends were the first commercial products to offer the pipe extruder a truly hard rigid material that was also tough. Besides their unique combination of hardness and high impact, these plastics have excellent chemical resistance and have a considerably lower specific gravity than any of the other rigid pipe materials. In addition, they have high heat distortion temperature and so retain usable strength at higher temperatures. In plant operations it has been found that the materials can be reprocessed without deterioration of properties, unless they are subjected to extreme conditions. The acrylonitrile copolymer-blend compounds thus offer an unusual combination of properties which has resulted in a continued rapid increase in the use of these materials for piping.

Cellulose Acetate Butyrate :—

Cellulose acetate butyrate gives what might really be called a semi-rigid pipe. It is intermediate in the field of non-flexible pipe materials in weight or density and has moderate chemical resistance, being decomposed by strong acids and alkalis. Although usually pigmented black, it can be produced as a clear transparent pipe, and this has opened up certain special applications. It has

generally good ageing characteristics, although even at moderate pressures and temperature the pipe tends to creep or increase in diameter. Cellulose acetate butyrate has been used extensively in the oil and natural-gas fields. It has been particularly useful in handling high paraffin crudes, where it shows less tendency towards paraffin build-up.

Polyvinyl Chloride :—

There are two main classes of rigid polyvinyl chloride pipe compounds currently in use, i.e., Type I " normal impact ", and Type II " high impact ". The latter is the latest addition in the U.S.A. to the field of rigid pipe manufacture, although materials of the normal-impact type have been used in Europe for almost twenty years. Polyvinyl chloride has a relatively high density, high strength, generally excellent chemical resistance, good ageing characteristics, and is self-extinguishing. Because of thermal instability at temperatures slightly above normal processing conditions, this material offers problems in the production of piping and fittings.

The Type I material may be relatively brittle and, under some conditions, particularly if reworked material is used, its chemical and solvent resistance may be affected. The Type II material is much tougher than Type I compounds but, because of added compounding ingredients, has slightly decreased chemical and solvent resistance. The long history of use of polyvinyl chloride in Europe has been restricted largely to chemical-plant installations. Its rapidly expanding use in the U.S.A. includes not only chemical-plant installations but also extensive application in oil fields as flow and brine disposal lines, for handling natural gas, and for many applications in the handling of clean or corrosive waters.

Polyvinylidene Chloride :—

Polyvinylidene chloride is probably the oldest thermoplastic pipe material in America, insofar as use is concerned. It has long been produced in heavy wall sizes for chemical plants or other locations where its excellent corrosion resistance outweighs the disadvantage of extreme brittleness. It has the highest specific gravity of the plastic pipe materials and a very high coefficient of thermal expansion. It has been joined by the use of threaded fittings and also by hot gas welding. This material is non-inflammable, and, in addition to its use as extruded pipe in the chemical industry, it has found considerable application as a chemical-resistant lining for steel pipe.

NEW DEVELOPMENTS

Several materials give promise of becoming factors in the field of plastic piping, details of these being as follows :

Low-Pressure Polyethylene :—

The low-pressure polyethylenes made by the various widely publicized new techniques will undoubtedly find some use as plastic piping. They are considerably stronger in short-term tests than standard polyethylene, but it now appears that the long-term effective tensile strength of the low-pressure materials is likely to be only about twice that of the standard material. Low-pressure polyethylene has a higher softening point than the standard polyethylene, but published comments on its heat resistance appear to be over-optimistic. Its increased stiffness will take it out of the class of flexible pipe into a semi-rigid type, so that insert fittings such as those used with standard material will not be satisfactory. This poses a considerable problem in the joining of pipe made with low-pressure polyethylene.

Irradiated Polyethylene :—

The exposure of polyethylene to high-intensity radiation brings about a type of " cure ", especially when the material is loaded with carbon black. Such cured material is more chemically resistant and has higher strength and less creep than standard polyethylene. Although the pipe is originally formed by thermoplastic extrusion techniques, the irradiation in effect thermosets the material, so that it will no longer melt. Irradiated polyethylene has been reported to have strengths as high as 500 psi at 300°F. The high carbon-black content of the irradiated material makes it electrically conductive, a fact which again sets it apart from most plastic materials. The economics of the irradiation process, and hence the eventual applicability in the field of pipe production, are still uncertain.

Fluorinated Hydrocarbons :—

Recent advances in the processing of tetrafluoroethylene and chlorotrifluoroethylene have aroused interest in these materials for use in pipes subjected to unusual corrosive conditions. Costs are still extremely high, compared with other plastic materials, so that the market will of necessity be relatively restricted.

Improved Materials :—

Considerable research is being expended in many laboratories on improvements in current pipe materials. Changes in the basic polyvinyl chloride polymer and methods of stabilization and internal lubrication can be expected to result in better PVC pipe materials. The acrylonitrile copolymer-blend system is an extensive family of plastics, and other members of this family will give stronger pipe materials serviceable over a wider temperature range. Modifications of current materials, such as the terpolymers of acrylonitrile, butadiene, and styrene, can be expected to give products with a new combination of properties which may prove valuable as raw materials for plastic pipe. The tremendous effort being put into the study of ethylene polymerization is expected to result in greatly increased knowledge of means of improving the overall performance of the various types of polyethylene.

Flow and Fracture

(*Concluded from page 570*)

initiated to investigate the possibility of making certain refractory ceramic materials which would be ductile at room temperature, and the early results have been encouraging. Many cubic ionic crystals have been tested, and to date all have been found to be ductile or capable of being made ductile at 70°F.

The most encouraging results of all are those obtained with magnesium oxide. Single crystals can be bent through substantial angles without fracture at room temperature, and surface elongations up to 20% have been obtained in some of the bend tests. There is a good chance that a number of useful ductile ceramic materials will be developed within the next few years.

Surface Rolling as a Method of Increasing the Fatigue Strength of Gears

By A. A. Novik and M. S. Balter. (From *Vestnik Mashinostroyeniya*, No. 10, 1957, pp. 65-68, 9 illustrations.)

The investigation described in this paper is concerned with the driven gearwheel on the bogie axle of a diesel locomotive. The wheel meshes with the pinion of the drive motor, which is supported by an elastic mounting on the cross-beam of the bogie frame. The diameter of the driven wheel is 750 mm, its module is 10 mm, the width of the tooth face is 140 mm, and the gear ratio is 4·7. As the driving pinion on the motor shaft is overhung, uniform pressure of the working surfaces is difficult to ensure.

The driving pinion is made of a case-hardened nickel-chrome steel having a surface hardness of at least 58 Rockwell C and a core hardness of from 35 to 45 Rockwell C. The driven gear is made of a cast steel containing 0·38–0·45% C, 0·6–0·9% Mn, 0·2–0·4% Si, 0·7–0·9% Cr, 1·5–1·9% Ni, 0·02–0·08% Ti, and a maximum of 0·035% P and 0·035% S. Heat treatment of the gear consisted of (a) normalizing and high-temperature quenching of the cast blank, (b) quenching and high-temperature tempering to a hardness of 255 to 302 Brinell, the ultimate tensile strength after this treatment being 90 kg/mm^2 and the impact value 3·5 kgm/cm^2, and (c) induction hardening of the tooth flanks to a hardness of 45 to 58 Rockwell C and subsequent low-temperature tempering.

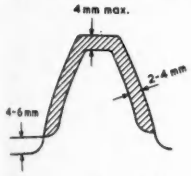

Fig. 1. **Profile of the induction-hardened layer in the central cross-section of a tooth.**

The profile of the induction-hardened layer in the central cross-section is shown in Fig. 1. Location of the boundary of the hardened layer from 4 to 6 mm from the bottom of the tooth space is intended to eliminate any possible detrimental effects of induction hardening on the bending strength of the teeth. Both sides of each tooth are hardened right through, as a result of the edge effect produced by the inductor coil, the depth of this hardened layer being about 8 to 12 mm. At one side, i.e., on the side remote from the drive motor, the hardened layer approaches the fillet.

After this locomotive had covered a distance of between 50,000 and 100,000 km, cracks were formed in the driven gears. These cracks were situated at the root of the tooth on the motor side and exhibited a typical fatigue pattern. No defects in material or heat treatment were discovered.

Inspection of the working surfaces of the teeth revealed non-uniform wearing in along the width of the tooth. At one end, the extent of the worn-in zone was large, while, at the other end, it disappeared completely. This was taken as evidence of substantial overloading of the tooth on the motor side.

Because the cracks were situated at the root of the tooth, it is natural to assume that, if this root (including the fillet) is treated by surface rolling, so as to produce residual compressive stresses, the fatigue strength of the gear can be substantially increased. In principle, the surface rolling process is accomplished by the rolling action of an appropriately profiled roller, suitably loaded and operating across the width of the gear.

Preliminary tests established the effectiveness of surface rolling of the tooth fillet. It was, however, necessary to design a machine for the surface rolling of gears and to develop a suitable rolling procedure.

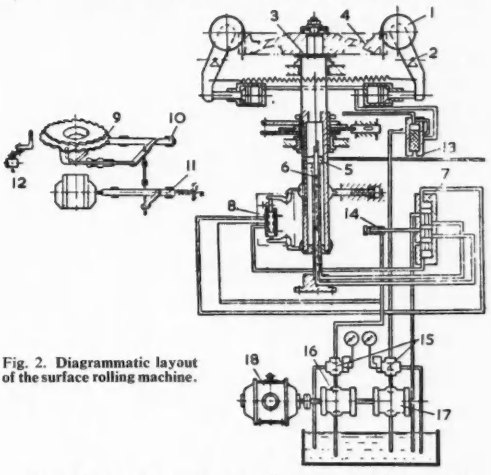

Fig. 2. **Diagrammatic layout of the surface rolling machine.**

In order to determine the effectiveness of the work-hardening procedure, it was considered essential to adopt simulated fatigue-test methods. Existing equipment obliged tests to be carried out on gears of the same module but of half the tooth width. The wheel diameter was reduced by a factor of 4·5, and the tests were conducted in a machine with a 30-ton pulsating load.

The special surface rolling machine was designed to the authors' specification, the general layout being shown diagrammatically in Fig. 2. Surface rolling is carried out simultaneously along two diametrically opposed tooth spaces by means of rollers (1) mounted on the upper parts of levers (2) attached to special sliding shoes. The required force is continuously applied to the lower ends of the levers (2). The simultaneous surface rolling of the gear at opposite points ensures a balance of forces in the machine as they arise during the rolling operation.

A vertical spindle (3) carries on its top journal the gear (4), which is clamped by a washer and nut before the machine is started. The spindle, controlled by a hydraulic ram, performs a reciprocating motion and is then indexed by one tooth until surface rolling of all the gear teeth is completed. When the gear is lowered, the bottom of the tooth space is pressed against rollers (1). The actual force transmitted to the surface is determined by the initial position of levers (2), which are adjusted before the commencement of the surface rolling operation, so as to ensure proper penetration of the rollers into the space between the teeth.

The reciprocating motion of spindle (3) and its periodic indexing are performed as follows :—The spindle itself is hollow and forms part of the hydraulic

system. A piston (5) is located in the spindle bore, and a rod (6), consisting of two tubes placed inside one another, is attached to the piston. Pressure oil is supplied from a vane-type pump (16), with a capacity of 25 litres/min, via a relief-valve (15) and a speed control valve (14) to a main control valve (7). Depending on the position of the main control valve, the pressure oil is conducted either into the upper or lower cylinder bore, causing a corresponding displacement of spindle (3). The position of this valve is determined by that of the spindle itself, the latter, at the end of each stroke, acting on the rockers of a pilot-valve (8) by means of special dogs located on the spindle. The pilot-valve (8) controls the position of the main valve (7), and the dogs also actuate a mechanism, comprising a ratchet and pawl (9), an index pin (10), and a push rod (11), for rotary indexing of the spindle. A limit switch (12) operates at the end of each work cycle. A special valve (13), supplied from another vane-type pump (17), with a capacity of 6 litres/min, via another relief-valve (15), is arranged to effect rapid withdrawal of the rollers from their working positions. Both pump (16) and pump (17) are driven from a common motor (18). Surface rolling of small-diameter gears was carried out on the same machine with the aid of a special additional fixture.

The roller profile was designed to ensure coverage by surface rolling of the entire transition surface between the flank of the tooth and the bottom of the tooth space (the zone of maximum bending stresses). At the root of the tooth, between the boundary of the induction-hardened layer and the surface-rolled zone, there is an intermediate zone which is not subjected to work-hardening. This, however, was not considered detrimental, as the intermediate zone does not contain stress concentrations. Two rollers of different profiles were used, one covering the bottom of the tooth space and the other the fillet.

In order to be able to produce substantial residual compressive stress at the surface and to achieve sufficient depth of work-hardened layer, high rolling pressures had to be applied. After a number of experiments, a pressure of 9 to 10 tons was selected, producing in the tooth spaces a residual deformation of about 0·4 mm. Indications of plastic deformation at the sides of the teeth were clearly visible.

The main purpose of the fatigue tests conducted was to determine the effectiveness of surface rolling by the procedure adopted. Most of the tests were carried out on the smaller gears, with a diameter of 150 mm and a width of 40 mm, made of cast-steel blanks similar to those used in the actual production of the driven gears. So as to be able to compare the endurance of cast and forged steel after induction hardening of their working surfaces, the core hardness and the profile of the hardened layer were made identical in each case, specimen gears of forged steel being hardened and tempered to the same hardness (269 Brinell) as that of the gears made from cast blanks. In addition, a second series of tests was carried out with segments cut from actual production gears made from cast and forged blanks of two different steels, as used in the manufacture of gears for a Russian diesel-electric locomotive.

To test the gears hardened by surface rolling, experiments were conducted to determine the separate effects of the profile of the induction-hardened layer in the vicinity of the sides of the teeth, i.e., the effect of the extension of the induction-hardened layer up to 2 mm from the bottom of the tooth space, and the effect of

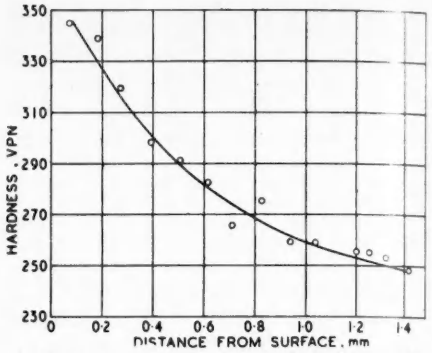

Fig. 3. Hardness measurements across the depth of the most highly work-hardened zone of a tooth.

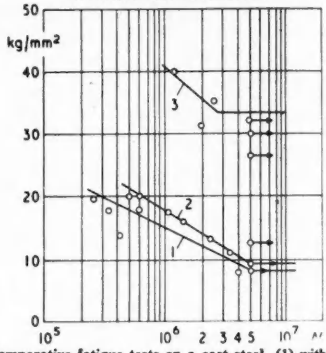

Fig. 4. Comparative fatigue tests on a cast steel, (1) without surface rolling and (3) with surface rolling, and (2) on a forged steel, without rolling.

through-hardening of the tooth sides over a depth of about 12 mm. Some of the gears hardened by normal shop procedure were tested in the middle part of the tooth along its width, 40 mm from each tooth side being cut away. In this manner, the effect of the induction-hardened layer at the sides of the tooth was eliminated. Another group of gears was cut in two, after induction hardening, so that the tests were carried out on components with only one tooth side hardened. In addition, one set of gears was first cut across the width into two equal parts and then subjected to induction hardening, producing through-hardening of both tooth sides.

After these tests, individual teeth were cut from the gears and examined to determine the degree of work-hardening by means of hardness tests over oblique cross-sections. It was found that the highest degree of work-hardening prevails in the fillet. Hardness measurements across the depth of the most highly work-hardened zone are shown in Fig. 3.

During the progress of fatigue tests, it was established that the cracks in work-hardened teeth were situated at the boundary between the work-hardened and the unaffected zones. Comparative results of fatigue tests for a forged-steel gear and for a cast-steel gear (with and without surface rolling) are shown in Fig. 4. It can be seen that the application of surface rolling considerably increases endurance. The effect is substantial and demonstrates the large reserve of strength which can be obtained by the use of surface rolling of tooth fillets in gears (and equally so in the case of other components of

(*Concluded on page 590*)

True Multi-Fuel Diesel Engines

By H. HOFFMANN. (From *Motortechnische Zeitschrift* (*M.T.Z.*), Vol. 18, No. 10, October 1957, pp. 311–317, 8 illustrations.)

To meet the requirement for engines capable of operating on cheap diesel oil in normal times and on any fuels available under emergency conditions, Daimler Benz have developed three 6-cylinder multi-fuel engines, their main data being as follows :—

Type	Bore × [mm]	Compression ratio	Rated bhp	Maximum torque [mkg]
OM321	95 × 120	26 : 1	110 at 3000 rpm	27 at 1600 rpm
OM315	112 × 140	22 : 1	155 at 2100 rpm	54 at 1400 rpm
OM326	128 × 140	22 : 1	160 at 2000 rpm	57 at 1400 rpm

These multi-fuel engines deliver, with hardly audible or measurable differences in running smoothness, the same power when operating either on diesel oils (e.g., gas-oil), or other fuels, including standard and high-octane petrols, petrol-benzol mixtures, jet fuels (kerosenes), alcohols, and even edible or lubricating oils. No additions of gas-oil or lubricating oil to the fuel are required, and there are no restrictions regarding octane rating of the fuel, provided that lead content does not exceed 0·08% by volume.

These engines are of the pre-chamber type. In conventional diesel engines the hard "hammering" noise noticeable when running on light fuels is due to late ignition and excessive release of energy through spontaneous combustion. Preliminary tests have shown that there is no problem with pre-chamber engines operating on gas-oil, jet fuels, or edible oils, but difficulties initially occurred (e.g., detonation, high-frequency oscillations, and lead corrosion) when operating on a high-octane leaded fuel, e.g., 89 octane petrol with an 0·08% lead content.

These difficulties were overcome, and combustion noise was very considerably reduced, by raising the temperature at the end of compression in order to shorten ignition delay. High air temperature in the pre-chamber at the end of compression makes rapid ignition possible, in spite of the differences in the chemical structure of the hydrocarbons. By means of preliminary reactions the hydrocarbons are decomposed into rapidly oxidizing oxygen-rich groups and in carbon-rich groups oxidizing at a slower rate. The oxygen in the pre-chamber air permits only partial combustion to take place. Owing to the rise in pressure, an intensive blow-down of the contents of the pre-chamber into the main combustion chamber occurs, resulting in intimate mixing with the unused air in the main chamber. The pre-chamber smoothes out the differences in the conversion of the hydrocarbons as regards velocity and the course of the reaction, so that the latter mainly yields carbon-rich groups, i.e., soot-like products.

The required increase in temperature at the end of compression was reached by raising the compression ratio by from 2 to 6, depending on the type of engine and shape of combustion chamber. Although the maximum cylinder pressures resulting from this change had no effect on the engine bearings, crankshaft, etc., further work was required in connection with the materials used for valves, valve guides, pre-chamber components, cylinder-head gasket, glow-plug, etc., in view of the high lead content of some of the fuels considered.

In addition, an electric fuel-circulating pump is fitted on the fuel tank; this pump is automatically brought into operation during starting and returns to the tank any vapour bubbles which may form on the suction side of the fuel pump. Under extremely unfavourable operating conditions (very high ambient temperatures), this pump can also be switched on manually. The injection pump is provided with an oil trap for the injector elements and the delivery plunger. The size of the injection-pump plungers had to be increased, to enable the engine to maintain the same power obtained with diesel fuel when running on petrol of lower calorific value per litre. The fuel filtering arrangements were improved by providing a system of two filters in series, so as to avoid any danger to the pump components when operating on petrol.

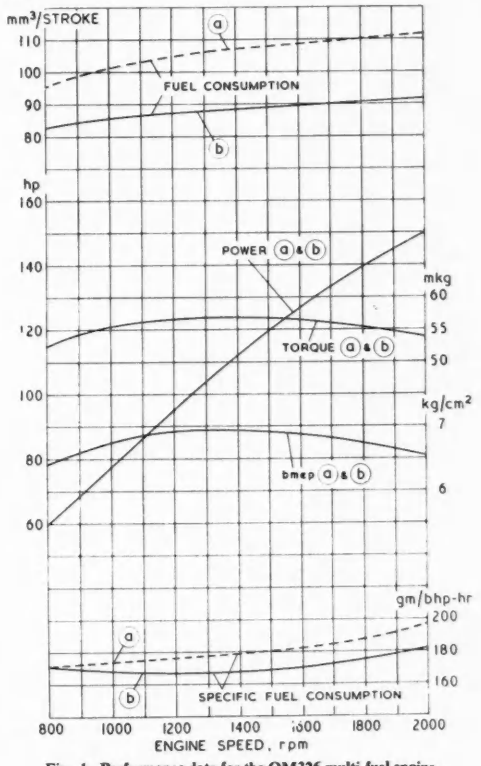

Fig. 1. Performance data for the OM326 multi-fuel engine.
(a) 89 octane leaded petrol.
(b) Gas-oil.

A series of tests was carried out on these engines, using, among others, fuels with specific gravities ranging from 0·725 to 0·788, aromatic contents from 14·75% to 49·5%, and octane ratings from 85 to 99. These tests provided additional evidence of the excellent flexibility of the pre-chamber multi-fuel engine under adverse load changes, typical performance figures for the OM326 engine being shown in Fig. 1.

There were no difficulties in normal starting, and the cold-starting properties of these engines were noteworthy. With normally operating glow-plugs, no additional heating devices are required down to about —20°C, using

a cold, half-charged battery. When the cooling water is warmed up, the engines can be started without difficulty at a temperature of — 40°C, using petrol, gas-oil, or other fuels. The required warm-up time for the cooling water, with a heater added to the cooling-water circuit of the engine, is at most 90 min.

The engines were run on test-beds and on the road, each engine completing about 27,000 km in country districts. One engine was run continuously for 1200 hr on a test-bed, followed by a further 600 hr, and then covered 70,000 km on the road. It was in the course of these various tests that the optimum materials were determined for the pre-chamber and for the valve arrangements. Wear of the chromium layer on the top piston-rings, and also therefore cylinder wear, is somewhat higher than in conventional diesel engines, without, however, having any effect on reliability. Initial difficulties in connection with fuel filtering, injection-pump wear, and distortion of the upper-ring groove in the piston were entirely overcome.

GERMANY

Assessment of the Durability of Crankshafts in Acceptance Tests

By A. T. WUPPERMANN. (From *Stahl und Eisen*, Vol. 77, No. 17, August 22, 1957, pp. 1117-1121, 7 illustrations.)

ADDITIONAL knowledge of the properties of materials and durability of crankshafts is required to accommodate the increased stresses associated with the higher charging pressures, higher speeds, and more compact construction of modern diesel engines.

A certain amount of information is provided by the standard tensile, notch-impact, and bending tests. In addition, non-destructive methods are being increasingly employed, e.g., magnetic powder methods to reveal surface cracks, or ultrasonic tests to indicate internal defects and inhomogeneities. However, interpretation and analysis of the defects indicated, particularly as regards their significance as possible sources of failure, have lagged considerably behind the progress achieved in flaw detection, etc.

As long as the influence of the various defects on crankshaft durability is not known, opinions will differ as to the extent to which such defects are permissible, but, from general considerations of production economy it does not seem reasonable to reject valuable crankshaft forgings solely on the basis of a somewhat subjective assessment, since in some cases, in spite of the flaws revealed, some crankshafts may be fully capable of withstanding the required stresses.

From metallurgical considerations, it is inevitable that, in the production of large forged crankshafts, depending on the size of the ingot, appreciable differences in strength are to be expected ; it is also impossible to remove all segregations, etc. from the shafts by machining. Tests by the magnetic powder method frequently show considerable accumulations of powder oriented in the direction of the fibres along the surface of the highly finished crankpins and journals ; on the web faces these appear as dots. In addition, some of the inhomogeneities inside the shaft revealed by ultrasonic methods occur in the core portion, i.e., near the centre-line, where there is little or no stress in torsion or bending.

The question as to what can be regarded as a permissible limit, from the point of view of reliability, has been the subject of investigations by Lehr[1] and Berg[2], who, during the war, initiated series of dynamic tests of partially defective crankshafts. The investigations described in the following can be regarded as a continuation of their work. In the present tests, the main new feature is that complete crankshafts, and not only sections thereof, are subjected to dynamic investigations. The crankshafts tested were supplied by various makers and had crankpin diameters between 130 and 240 mm, with overall lengths of 1·5 to 4·5 metres and weights ranging from 500 to 2500 kg.

Under service conditions, crankshafts are required to sustain combined stresses in bending and torsion, the bending stresses being caused by shear forces resulting from the piston loads, and, in absolute values, being much higher (by about 50%) than the torsional stresses. To keep bending stresses at low values, it is necessary to ensure that the alignment of the bearings supporting the various crank-throws is as accurate as possible and that the bearings are properly maintained during service. The vital importance of bending stresses on crankshaft durability is a subject which has also been extensively investigated[3].

Torsional stresses in crankshafts are due to the cyclically varying transmitted torque. Under conditions of resonance in the system (consisting, for instance, of the engine, a propeller shaft, and a marine propeller), considerable torsional vibrations may develop ; these can, however, largely be reduced by means of vibration dampers.

The purpose of the investigation was to clarify, as far as possible, the following questions :—

(1) Do longitudinal defects give rise to fatigue fractures ?
(2) If not, where are fatigue fractures mainly initiated?
(3) How do these fractures propagate ?
(4) What is the relation between stress and durability?

From these questions, it can be seen that the main object was not so much the study of crankshaft stresses under operating conditions as a determination of the effect of irregularities in the material on durability.

Generally, defects in forged crankshafts, as revealed by the magnetic powder method, are in the longitudinal direction. The possibility that these may cause rupture of the shaft can be verified only by dynamic torsion tests.

Under the action of alternating shear stresses, axial surface cracks on crankpins or journals branch out in the directions of the maximum principal stresses, i.e., at 45 deg. to the shaft axis. When bending stresses are applied, this branching out of longitudinal defects cannot be expected to occur, since the bending fracture is perpendicular to the direction of the defect and hence should not be influenced by it. The shafts were therefore tested by applying alternating torques.

The available crankshafts were of various sizes and types and had most of the typical defects likely to occur in such forgings ; in some cases the defects were com-

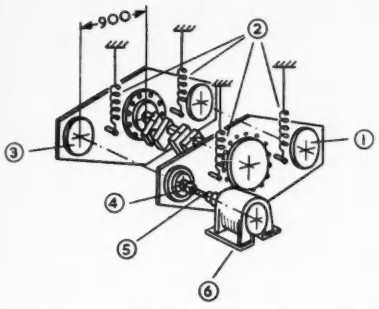

Fig. 1. **Schematic arrangement of rig for dynamic testing of crankshafts.**

paratively large, whereas in others they were minute.

A diagram of the test arrangement employed is shown in Fig. 1. The ends of the crankshaft to be tested are bolted to large metal slabs serving as torque arms with additional compensating masses (1) and (3) to obtain the required polar mass moments of inertia. These torque arms are suspended on helical springs (2) attached to an overhead rigid structure. The vibratory system (the crankshaft being regarded as a torsional spring between the torque-arm inertias) is thus provided with a " floating suspension ", which avoids any constraining forces or couples that might otherwise be superimposed on the applied torque. The vibratory torque is generated by the centrifugal force of a mechanical out-of-balance type of exciter (4) fitted at one end of a torque arm and driven through a cardan arrangement (5) by a variable-speed d.c. motor (6). By varying the speed of the latter, the excitation frequency can be adjusted as close as desired to the natural frequency of the whole system, so that resonant or nearly resonant vibrations of considerable amplitude are produced.

In a preliminary test with one of the torque arms clamped, each crankshaft was subjected to a static torque to determine its torsional stiffness. This value enabled the dynamic torque, applied in the subsequent tests with the freely oscillating arrangement, to be determined directly as the product of stiffness and the measured vibration amplitude at one of the torque arms. The set-up is therefore very simple, and the dead-weight of the crankshaft is taken by the floating suspension. The vibratory torques are fully controlled by adjusting the speed of the motor.

Altogether, fourteen crankshafts were tested to rupture in these torsional-vibration tests. Information on the crankshafts investigated is summarized in Table I.

The tests were carried out with gradually increased values of stress level. It was not possible to produce Wöhler curves, owing to the lack of a sufficient number of test-pieces (complete crankshafts) of identical shape and material ; moreover, for Wöhler curves it would be necessary to have similar patterns of defects on the corresponding crankshafts.

The various stages of a test on crankshaft No. 12 are shown schematically in Fig. 2, in which the upper portion shows the positions of the torque arms, and the lower portion the gradual increase in stress level or torque during the total period of testing.

Generally, the tests were initiated with a stress level of ± 4 kg/mm^2, which corresponds approximately to the upper limit of estimated service stress.

The dynamic torque acting on the crankshaft was not only determined from the vibration amplitude but also indicated directly by means of strain-gauges situated on the journals or crankpins ; the strain-gauges were calibrated in the static test, and their output was displayed on an oscilloscope screen.

The stress level for each stage of the tests was maintained at a constant value for at least 20 million cycles (and extended to 30 million cycles in most cases) ; after completing this stage, the stress level was increased by 1 kg/mm^2, or less at the higher levels. In all cases the stress values mentioned refer to the nominal crankpin stress, which is used in design-stage estimations. The tests carried out in this manner took a considerable period of time ; in the example in Fig. 2, approximately

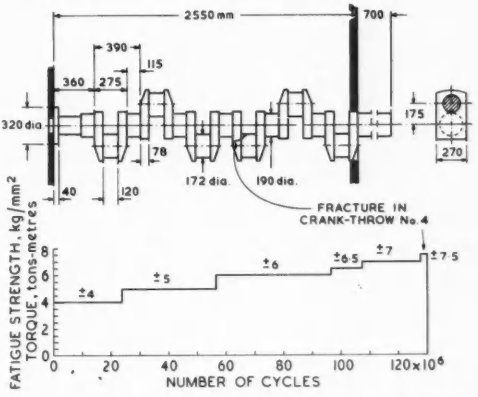

Fig. 2. **Diagram showing values of applied torque during the various stages of the test on crankshaft No. 12.**

130 million load cycles were required. For this test, therefore, which went on day and night without interruption, the total period of testing, with an excitation frequency between 800 and 1000 vpm, extended to about 100 days. To speed up the work, it was therefore necessary to build a second dynamic test rig, which was completed soon after the work had been initiated.

TABLE I. DATA AND TEST RESULTS FOR THE VARIOUS CRANKSHAFTS INVESTIGATED

Crankshaft No.	Type of Steel		Crankpin		No. of throws	Stress level [kg/mm^2]	Test Results	
	%C	U.T.S. [kg/mm^2]	Outer dia. [mm]	Bore dia. [mm]			No. of cycles to fracture $\times 10^6$	Position of fracture in crankpin
1	0·53	70	130	—	6	±2 to ±15	24	No. 2, bore
2	0·40	58	150	75	6	±3 to ±13	7	No. 4, fillet
3	0·37	60	150	75	8	±5 to ±7	76	No. 2, fillet
4	0·46	70	180	—	4	±5 to ±8	45	No. 2, fillet
5	0·37	58	190	—	8	±5 to ±6	41	No. 3, fillet
6	0·33	64	200	—	6	±4 to ±6	78	No. 3, fillet
7*	0·40	79	145	—	4	±5 to ±7	10	Nos.2&3bores
8	0·35	57	190	85	6	±5 to ±7	92	No. 3, fillet
9	0·41	58	215	100	8	±4 to ±6	63	No. 4, fillet
10	0·42	66	180	—	6	±4 to ±7	98	No. 6, fillet
11	0·44	69	150	80	6	±4 to ±7	117	No. 1, fillet
12	0·22	48	172	—	6	±4 to ±7·5	130	No. 4, fillet
13	0·30	60	180	100	4	±4 to ±6	78	No. 2, fillet
14	0·40	64	215	100	8	±2 to ± 4	94	**

* Crankshaft No. 7 surface-hardened.
** With crankshaft No. 14, stress was applied in bending, and the position of fracture was in all webs. With all other crankshafts, stress was applied in torsion.

Position of Fractures

In all cases, the torsional fatigue fracture occurred at the crankpin. As a rule, it proceeded from the crankpin fillet. In most cases the fracture also extended into the web, and generally the web broke through the weaker section of its bevelled end.

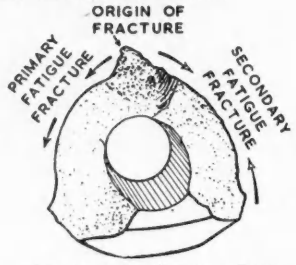

Fig. 3. Details of fracture in the test on crankshaft No. 8.

An example of such a fracture, which occurred in crankshaft No. 8, is reproduced in Fig. 3. Originating at the fillet between the web and the crankpin, the fracture progresses through the crankpin as a smooth helical fracture and emerges in the bevelled section of the opposite crankweb. In the second stage of its development, the fracture proceeds from the broken web and is completed, through the remaining crankpin section, when it travels back to the original cross-section of the initial failure.

Under high dynamic torque, the filleted transitions showed multiple shear-stress cracks. From the dimensions of the crankshafts investigated, the stress-concentration factors for the fillets were evaluated and found to be between 1·5 and 1·8, so that the fillet stress was between 50% and 80% higher than the nominal stress, used as a reference value in the tests. Initial cracks or fissures first occur at these positions of increased stresses.

Crankshafts also have transverse holes in the crankpins for the supply of lubricating oil. These holes disturb the smooth " flow of stresses " and might therefore also be expected to be a cause of fatigue failures.

Of the fourteen crankshafts investigated, nine had been fully machined and provided with oil holes in the crankpins. In three of these shafts the fracture passed through the crankpin oil hole, but only in two of these cases did the fatigue fracture originate at the hole. In the third case, it definitely spread from the fillet. One of the two typical oil-hole fractures was found to originate not at the edge of the hole but at a tool-mark inside the oil hole and about 15 mm below the crankpin surface.

In another case, at a nominal stress of ± 7 kg/mm^2, incipient cracks were detected at the edge of the hole, but these did not lead to fracture. From the above, it can be concluded that considerably greater importance should be assigned to the fillets than to oil holes as possible origins of fatigue failures.

Limiting Stress and Endurance

It was found that with fairly rapidly increased stress levels the fractures occur at considerably higher stresses than when intermediate stress levels are maintained for appreciable periods. The tests, therefore, were carried out for long periods of time at each stress level, so that any short-time influences would be eliminated.

It was considered of particular importance to conduct the tests at nominal stresses not greatly superior to those expected to occur in service. These stresses are encountered in service during brief periods, for instance when passing through critical speeds. Exceptions were made only in the two preliminary tests on crankshafts (1) and (2), with rapidly increased stresses, resulting in rupture after 7 million and 24 million cycles respectively. The limiting stresses in these cases were ± 13 and ± 15 kg/mm^2 ; owing to the internal (hysteresis) damping of the material, these two crankshafts reached temperatures of the order of 150°C.

From the test results, it appears that nominal stresses exceeding ± 6 kg/mm^2 can be regarded as critical. This also is in agreement with the limiting values indicated by Dorey[4].

Behaviour of Axial Defects under Vibratory Torsional Stresses

The longitudinal defects revealed by the magnetic powder method showed considerable differences in behaviour under the various stress levels. The result was in no case in agreement with the estimated importance of such defects, based on external appearance.

" Genuine " defects (i.e., definite discontinuities reaching up to the surface) showed signs of considerable working under alternating torsional stresses. This was rendered visible by bubbles formed after pouring petrol over the defective areas, and by the fine residues produced by fretting corrosion occurring in these areas.

Long axial cracks branched out at their ends in several instances, as previously stated, when the torsional stress level reached values of ± 6 to ± 7 kg/mm^2. However, in all cases, even with very extensive axial defects, the spread of the branched portions eventually ceased, i.e., after some period of time. It seems that there is a stress-relieving action in this case, which, owing to the bifurcations in the defective area, tends to prevent, for some time, a further extension of the defect.

Axial defects did not become starting points of fatigue fractures in any of the crankshafts investigated. This does not mean that they should be completely disregarded, but it should help to alleviate some excessive objections previously raised as to the importance of such defects and also to prevent unduly severe requirements which might impede the economical production of forged crankshafts.

Conclusion

The test results clearly show that an increase in the fatigue strength of crankshafts is not so much at present a question of material as of suitable design features. Both the torsional tests and the dynamic bending tests gave ample evidence that stress raisers in transitions and other unfavourable shape or design factors are the origins of fatigue fractures.

It is also considered that the importance of inclusions in the crankshaft material is also sometimes overestimated ; the view expressed is that inclusions can be regarded as acceptable if their stress-concentration factors are not greater than those of the transitions, i.e., fillets etc., normally found in crankshafts. It would be useful if further dynamic tests could also be undertaken to obtain quantitative data on this subject.

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British Industrial Developments

Computer-Controlled Automatic Flame Profiling of Steel Plate

Based on the assumption that a method was required of direct transfer of information from the drawing-office to the cutting machine without the need for precision drawings and photographic scaling down, and that the system itself, and hence the design of machine used, must be freely adaptable to any sequence control for the marshalling and flow of material into the cutting area of the machine, a new computer-controlled automatic flame-profiling system for steel plate in shipyards has been developed and demonstrated by British Oxygen Gases Limited, of London, S.W.1.

As shown in Fig. 1, the essential stages of the system are as follows :—

(a) Preparation of a drawing (1) of the part to be cut. This is done in the conventional manner, except that all dimensions are given in co-ordinate form relative to a datum located outside the profile.

(b) Preparation of a planning sheet (2), in which the dimensional information from the drawing is entered in the correct sequence. Details of kerf width and cutting speeds are also included. It should be noted that it is necessary to specify only the dimensions for change points on the profile, i.e., points at which there is a change of direction, such as at corners, junctions of circular arcs with straight lines, etc.

(c) Encoding the planning-sheet information (3) into the form of punched paper tape for use as input to the computer. A teleprinter for standard 5-hole paper tape is used for this purpose, and copy-typing only is involved. A conventional typed sheet is simultaneously produced for checking against the original planning sheet.

(d) Feeding the paper tape into the computer (4), where the continuous path of the cutter from change point to change point is computed and this information recorded in pulse form on magnetic tape. It is not envisaged that organizations using automatic flame-cutting machines would own a computer, but a centralized computer service would be available where users can purchase time, as required.

Fig. 2.

(e) Playing back the magnetic tape in a control console (5), which contains a tape deck and suitable amplifying equipment for converting the pulses on the magnetic tape into command signals which are fed to servo-motors

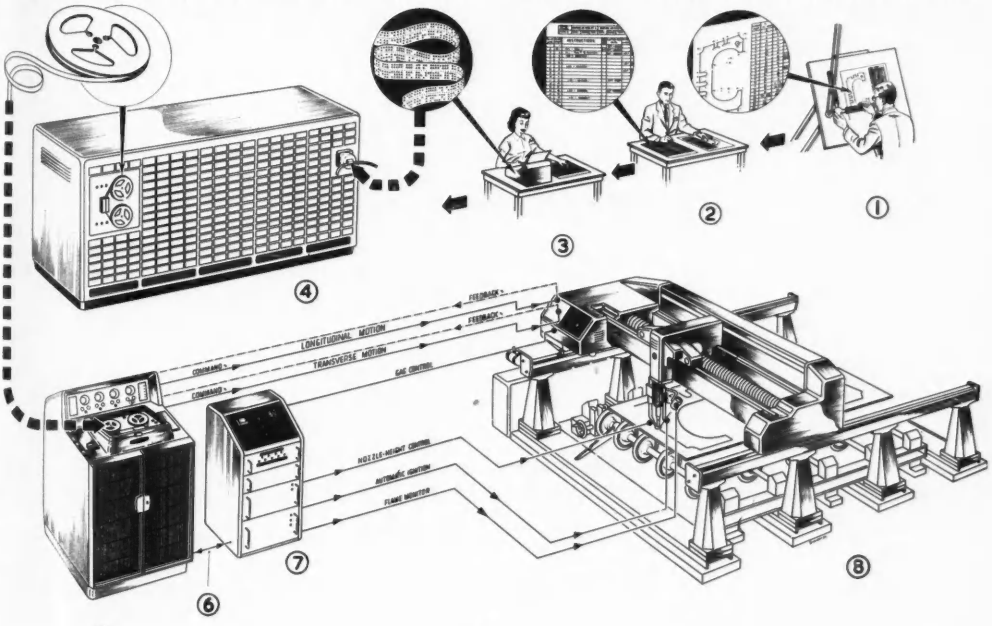


Fig. 1.

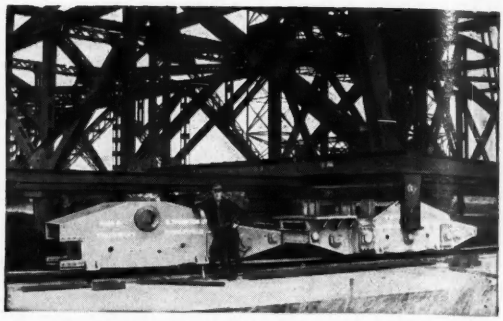
HOFFMANN CAN TAKE IT

This vast-2,000 ton structure, the world's largest telescope, revolves on Hoffmann Bearings.

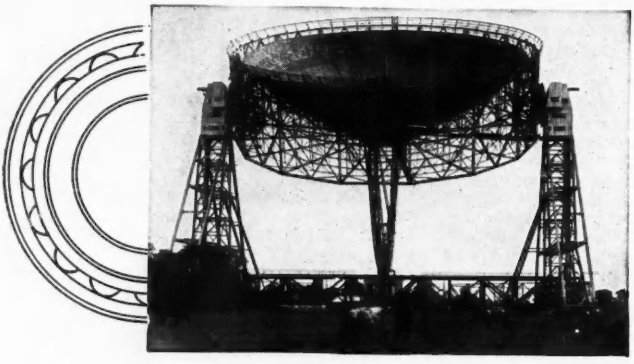
The centre pivot made by **Davy and United Engineering Company Limited,** is a pintle mounting using one large double-row roller bearing, and one large single thrust ball bearing, the roller bearing being 42" in diameter

Carrying the whole structure in its circular track are twelve 20-ton bogies made by **B. Thornton Ltd., Engineers of Huddersfield.** Each bogie is fitted with four wheels and each wheel with two parallel roller bearings and one ball location bearing.

The telescope can be steered to any point in the sky and will greatly increase our knowledge of radio waves reaching the earth from the farthest known nebulae in space, as well as meteors, the aurora borealis, the moon and the sun.

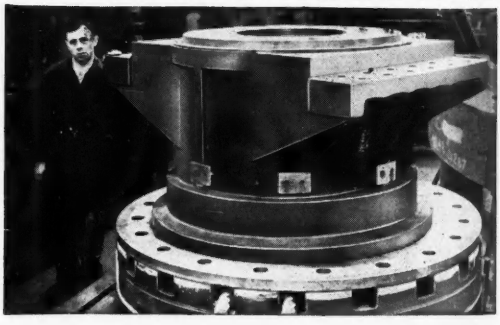


TWO OF THE TWELVE 20-TON BOGIES BY B. THORNTON LTD. ENGINEERS



HUSBAND AND COMPANY WERE THE CONSULTING ENGINEERS TO MANCHESTER UNIVERSITY WHO NOW OPERATE THIS GIANT RADIO TELESCOPE AT JODRELL BANK, CHESHIRE

THE 13½-TON CENTRE PIVOT BY DAVY & UNITED ENGINEERING CO., LTD.



HOFFMANN

parallel

ROLLER BEARINGS CARRY THE WHOLE LOAD

THE HOFFMANN MANUFACTURING CO. LTD., CHELMSFORD, ESSEX

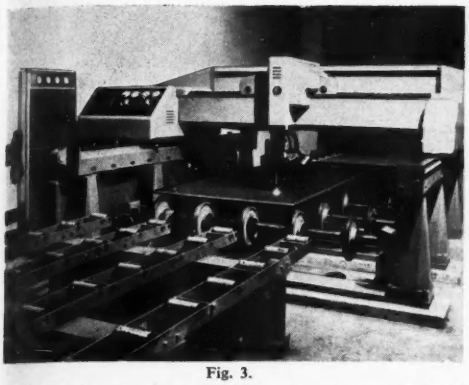


Fig. 3.

on the *X-Y* axes of the machine. Sequence control (6) and an auxiliary functions console (7) are also provided. The tape control console and auxiliary functions console are illustrated in Fig. 2, in which the lid of the tape deck is shown partially raised, and three trays, each of which contains six card-type circuits, are partially withdrawn. The underside of one of the chassis in the auxiliary functions console can also be seen.

(f) After the tape deck has been started, the information passes to the automatic flame-profiling machine (8), which then proceeds under the control of the magnetic tape alone, no human intervention thereafter being necessary. A front view of the experimental computer-controlled flame-profiling machine, with a simplified version of a plate-handling roller table, is shown in Fig. 3.

In addition to positional control of the cutter, certain other control elements (Fig. 1) are provided to cover requirements peculiar to the flame-cutting process, these being (a) continuous nozzle-height sensing, in order to preserve the correct distance between the cutting nozzle and the plate ; (b) a flame-monitoring unit to confirm the presence of the preheat flame and the continuity of the cutting process, so that, in the event of loss of cut or flame failure, the machine is automatically shut down ; and (c) an automatic ignition system for lighting the preheat gases. A view of the transverse carriage and cutter head is given in Fig. 4, and shows (left to right) the nozzle-height sensing probe, the cutter, the ignition electrode, and the flame-monitoring unit.

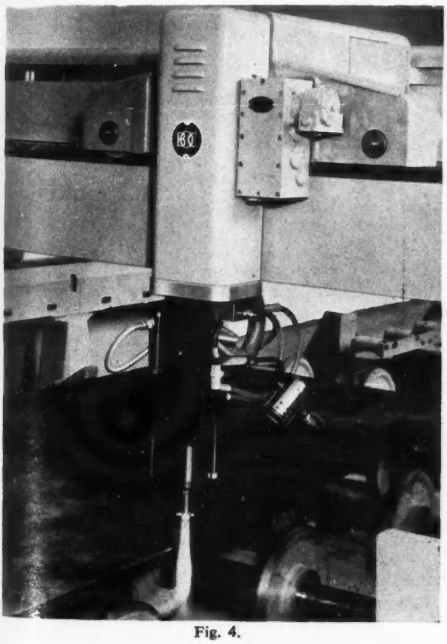


Fig. 4.

Finally, there is automatic continuous monitoring of the control unit, so that if for any cause, such as supply or component failure, some part of the equipment ceases to function, the machine will shut down before any damage is done to the work. It should be noted that tape control is at present visualized for profiling, as distinct from rectilinear plate preparation. The latter will be catered for by automatic sequence control of the portal-type " Oxyplane " machine for straight edge preparation, with manual setting of cutters to accurate scales on the machine.

It is realized, of course, that, in the application of the system to shipyards, there are many problems, among which are layout and availability of space, which only the shipbuilder can define and answer in detail in his examination of the practical development of such a system. Nevertheless, it seems clear that the line of approach followed in this system coincides with trends in shipyard layout which are even now being established. Indications are that these new concepts will be as readily explored by shipbuilders in Great Britain as they appear to have been on the Continent and elsewhere. Furthermore, as development of the machine proceeds over the next year or two, the co-operation of shipbuilders on the design of the machine, Ferranti on computer applications and control systems, and specialist conveyor manufacturers on the plate-handling problem should lead to a quick and satisfactory solution of all the problems to which this project will give rise during the course of its development.

Prefinishing Chromate Oxidization Coating Process

Aluminium castings are being given a chromate oxidization coating by a new type of plant, recently installed by Woods of Colchester Ltd. Paint, lacquer, and enamel are liable to lose their adhesion to aluminium and its alloys, and consequently fail by peeling, flaking, or chipping. With the chromate oxidization process (C.O.P.), the natural oxide film is replaced by an insoluble granular aluminium oxide coating, which provides improved paint bonding and anti-corrosion resistance. This process has been used extensively for treating aluminium sheet and panels, but has not hitherto been employed for castings.

The Woods plant, which is intended to replace prime-painting and stoving, is operated by two men and has an output exceeding that of the seven painters previously engaged on prefinishing. The result has been a cut in production costs and improved products. Handling 13 tons of impellers, motor carcasses, and covers, together with other aluminium components, in a 44-hr week, the Woods installation is the first continuous plant to be designed for use in conjunction with the C.O.P. process. Gravity, pressure, and sand castings and sheet-aluminium components are being treated. The overall dimensions of the plant, which was designed in co-operation with Woods by the Jenolizing Co. Ltd., who provided the C.O.P. solution, are 35 × 8 × 10 ft high.

The plant consists of three tanks, of which the first holds 1000 gal of C.O.P. solution, the second is a running cold-water rinse of 500 gal capacity, and the third a hot-water rinse of the same capacity. Castings are suspended on jigs or in wire-mesh baskets from a flight bar conveyor. Travelling on the conveyor at 6½ ipm, the castings are suspended in the C.O.P. solution for 15 min. They then pass through a cold-water curtain, which reduces the amount of drag-out from the solution, before being dipped successively into the running cold-water rinse

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and hot-water rinse tanks. The hot-water rinse ensures the necessary rapid drying of the castings. Both the C.O.P. and hot-water tanks are steam-heated, the former to between 92 and 98°C, and the latter to 70°C. Compressed air is used to agitate the C.O.P. solution and cold-water rinse.

The strength of the solution is tested twice a day, and the tank is cleaned out about once a fortnight to remove the aluminium and chalk which settles on the bottom. To facilitate cleaning, a self-priming pump, with a capacity of 1000 gph, is fitted, the solution being transferred to the empty cold- and hot-water tanks. Vigorous gassing occurs during treatment, and the tank is provided with fume extraction. A similar arrangement extracts steam rising from the hot-water tank.

Low-Pressure Polythene Sheet

The latest of a large group of plastic sheeting materials developed by Iridon Limited, of London, W.1 is Iridon-LP1300, which is a polythene sheet of the low-pressure type, based on the Ziegler process. Sheets of this type may be vacuum-formed or fabricated, as required, by welding, a present important application being for ducting. The most outstanding characteristic of this material is the very small amount of branching along the molecular chain, so that the macromolecule is built up in a linear manner. Its typical properties are therefore high stiffness and strength, good surface finish, and a high softening range.

The melting range is approximately 125 to 135°C. The practical possibilities of utilizing this high melting range are, as with all thermoplastics, markedly dependent on the duration of the heating and also on any mechanical stress which may be present at the same time. These factors in certain cases limit the working temperatures to values which lie far below the melting range. On the other hand, heating in the neighbourhood of sterilization temperature is possible. At low temperatures, the material stiffens only below —30°C. At temperatures above these it displays outstanding toughness. These temperature properties, together with its good tensile strength, excellent elongation at break, and high impact strength, make it a suitable sheet material for a large variety of applications. Furthermore, it is not affected by water and is resistant to a large number of chemicals, in addition to having a very low water-vapour permeability and a low permeability both for materials causing aroma and for gases such as oxygen, carbon dioxide, and nitrogen.

Obvious fields of application are those where high softening temperature, increased toughness, strength, chemical resistance, and decreased permeability to liquids and gases are important. Hospital and dental instrument trays offer an immediate outlet, as sterilizing by boiling has no detrimental effect on the material, provided that the component has been formed without excessive stress. Similarly, food factories have a ready application for containers used in the preparation of tinned and frozen foodstuffs.

Iridon-LP1300 has been specially developed for vacuum-forming and, owing to its special properties, it can be deep-drawn without the excessive thinning normally associated with the ordinary grades of polythene. Correct heating of the sheet is important, and, where thicknesses of 0·080 in. and over are used, it may be necessary to employ top and bottom heaters. Where this is not practicable, the heating cycle should be extended to distribute the heat evenly throughout the sheet. It may be even necessary, when using a single heater, to spray the side nearest the heater momentarily with a jet of cold air, in order to reduce the temperature of the upper surface to approximately that of the lower. This will avoid undue strain in the sheet during the forming process.

Portable Mechanical Double-Action Resuscitator

Expected to prove of real value in cases of drug and gas poisoning, drowning, electric shock, etc., the "Minuteman" portable mechanical double-action resuscitator, originally developed and already in extensive use in the U.S.A., is now being marketed in the U.K. by the Medical Division of British Oxygen Gases Limited. The machine weighs only 28 lb and is contained in a case of small dimensions, so that it can be carried quickly to the scene of an accident. In addition, it is robust, simple to operate, requires less skill and energy than any other modern methods of resuscitation, and can be used in confined spaces such as pit shafts or even under debris. Another advantage is that it can also be used for patients with fractured ribs, eliminating the dangers occasioned by manual resuscitation in such cases.

Until recently, all portable resuscitating machines were only of the single-action type, whereas, to be truly effective, a resuscitator should have a double action, i.e., it should ventilate the lungs in a regular and efficient way, to ensure that sufficient oxygen is carried to the blood and the waste gases removed, and it should support failing circulation by assisting the return of blood to the heart. In the "Minuteman", the double action is automatically controlled by the patient's lung capacity. When a certain pressure has been reached, lung inflation stops automatically, and suction then draws the used gases

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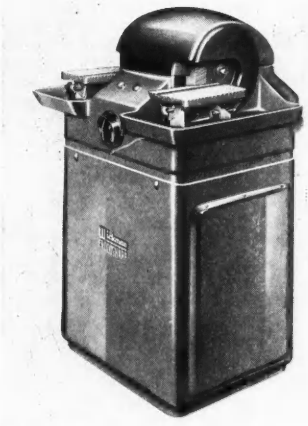
from the lungs. This action of sucking air from the lungs draws blood into them from the rest of the body, assisting in the return of blood to the heart. Attached to the midget breathing mask, which is held in the hand, is a valve, and the power which operates it is derived from the pressure in an oxygen cylinder packed in the case.

A suction catheter attached to the machine can be used to clear obstructing mucus and froth. If necessary, the machine can be made to act as an inhaler, delivering oxygen-enriched air to a conscious patient. The special pressure requirements of rib injury can be met by simple adjustments. Extension leads permit the mask to be used at a distance from the carrying case. If required, two of these resuscitating face-masks can be operated from the same source, so that two patients can undergo treatment at the same time.

Spark-Erosion Tool-Grinding Machines

Developed from the earlier machine, the "Erodosharp" Mark II tool-grinding machine, announced by Wickman Limited, of Tile Hill, Coventry, embodies two major refinements in design, i.e., two revolving electrodes and adjustable tool-rests are now provided, and an extractor fan is built into the machine base, so as to enable fumes produced during processing to be ducted to atmosphere independently of other extractor systems.

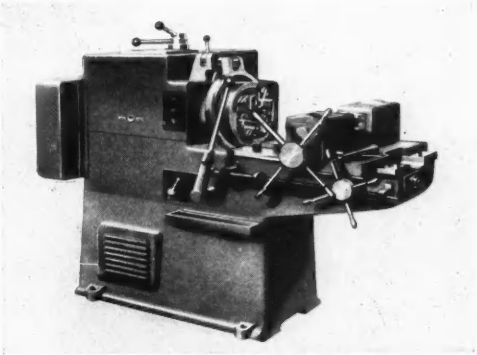
In appearance, the machine resembles a conventional grinder, except that two revolving iron wheels constitute electrodes, and metal particles are removed from the tool by the effects of a controlled electrical discharge between the electrode and tool across a dielectric gap which in this case is a thin film of oil on the revolving, electrode. The actual tool-grinding process is performed in the same way as on conventional machines, except that no pressure is required. The largest single economy effected by this method is, however, the direct and immediate saving in diamond-wheel costs, inasmuch as with the exception of the lapping of superfine cutting edges, the "Erodosharp" will achieve all the results obtained with diamond wheels at a fraction of the cost.



Since there is no physical contact between electrode and tool, there is no load on the wheel, no wear due to abrasion, and no heat generated in the tool. This means that the tip and shank of carbide tools can be ground together, without any risk of the tip cracking from thermal shock. The conventional method of using different grinding wheels for roughing and finishing is eliminated, finish selection being simply effected by operation of a three-position switch, which also gives a faster cutting rate for roughing.

Single-Spindle Screwing Machi

Redesigning of the range of single-spindle tangential die-head screwing machines produced by Joshua Heap & Co. Limited, of Ashton-under-Lyne, has recently been completed by the introduction of a machine fitted with a 3-in. or 4-in. tangential die-head, which will thread bolts from $\frac{1}{8}$ in. to 3 in. and pipes from $\frac{1}{8}$ in. to 4 in. The machine is fitted with a heavy-duty all-geared nine-speed headstock, which is amply rated to transmit full power at low spindle speeds, while the extremely wide range of spindle speeds available enables the machine to cut all classes of material throughout the entire range. The final drive to the main spindle is via a pair of constant-mesh helical gears, thereby ensuring a smooth transmission of power.



The machine illustrated is fitted with a centrally mounted lead-screw, which is essential when screwing very coarse threads which have to be cut in two passes. Alternative lengths of bed can be supplied, so that either 15 in. or 36 in. can be screwed at one setting of the vice. The open-jaw self-centering vice is of box pattern, as fitted to all machines in this range, and is extremely powerful. All the operating mechanism is totaly enclosed, protecting it from damage and wear from swarf. Two pairs of vice jaws are used, ensuring a perfect grip on bolts or pipes.

The tangential die-head fitted is the standard Heap head, of which one of the main features is the cam ring completely surrounding the die-holders and absorbing all cutting strains. This head is fitted with automatic opening and closing through the saddle movement, as well as hand operation by a lever on the side of the machine. A double-cut device is also fitted, so that a thread can, if required, be cut in two passes without stopping the machine.

Multi-Pole Contact Connectors

A new and comprehensive range of plugs and sockets, to be manufactured in the U.K. under licence from Tuchel Kontakt, of Germany, is announced by the Contact Connectors Division of Modern Acoustics Limited, of Boreham Wood, Herts. The patented contact principle employed in this new range of connectors differs radically from more traditional systems, inasmuch as their construction is based on the theory that surfaces kept free from oxide film and dirt are even more important factors than contact pressure.

Basically, the contact consists of a series of tubes of decreasing diameters, open longitudinally with two or more transverse slits, assembled one within the other. In operation, the bevelled contact blade is inserted into the first of three split cylindrical spring banks and, as the blade is thicker than the gap, the spring assembly is forced apart and each of the springs grips the blade in pincer fashion. As the blade is introduced, the front

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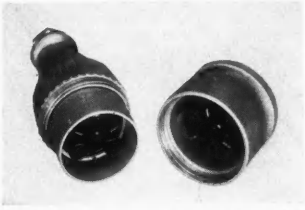
edges of the spring assembly rub against it, cutting through existing dirt or oxide film. This process is repeated through the other two banks, until the contact blade is fully inserted. An interesting feature is that the spring banks are not rigidly secured, but float in the connector assembly, ensuring that the pressure exerted by the individual springs on each side of the contact blade is always balanced. Other important features are a multiple number of independent contact points for each pole; low contact resistance with large contact area, unaffected by vibration and effective over a wide range of temperature; and simple engagement or disengagement.



These connectors are produced in a wide range of shapes and sizes, i.e., rectangular, cylindrical, etc., and from small $\frac{3}{4}$-in. diameter 6-pole units, or less, each carrying 5 A at 125 V, to larger 5-in. diameter units with 36 poles per unit, each carrying 60 A at 500 V. A typical 6-pin, 20-A, 1000-V heavy-duty connector is illustrated.

Oil-Resistant Plastic Transmission Belts

A further development in plastic power-transmission belting has been introduced by R. & J. Dick, Ltd., of Glasgow. The new belt, known as " Dixylon-Suplex ", is oil-resistant and is particularly suitable for application in the machine-tool industry, since it largely retains its coefficient of friction, even under the oiliest running conditions. It also possesses anti-static properties and is, in addition, resistant to abrasion.

The properties of high tensile strength and resistance to stretch and heat, found in standard Dixylon, are also characteristic of the new belting, which is ideal for high-speed drives up to 10,000 fpm, especially where small-diameter pulleys and short centres are involved. Moreover, because of its great strength and light weight, pressure on bearings is markedly reduced, while its flexibility and resistance to abrasion make it eminently suitable for use on " untwister " drives in the textile industry. It can easily be made endless in 15 min with simple tools, and the resulting joint is even and flexible, ensuring smooth running without " knocking ". Various weights and thicknesses are available, to meet the demands of different drives.

Two-Speed Drill with Percussion Attachment

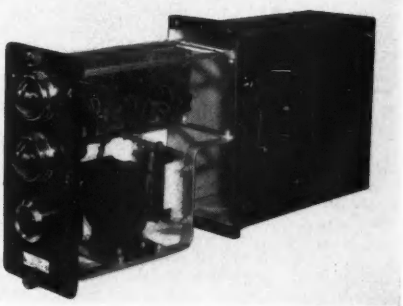
A new type of two-speed drill, designated " Duax " and manufactured in Germany by Hahn & Kolb, is now marketed in the U.K. through the main distributors, Trend Industrial Equipment Ltd., of Stanmore, Middlesex. The drill, which is available in two sizes, is extremely adaptable and incorporates a two-speed selector switch which enables the correct speed to be chosen to suit the material and size of drill bit. An additional advantage is the provision of a percussion drilling head of special design, which can be clamped to the head of the tool in a few seconds. This attachment converts the tool into a hammer drill, giving 9000 impacts per minute, for making holes in tiles, concrete, and brick. It is stated that, with the combined impact and rotary movement produced by the percussion head, drilling speeds can be increased by as much as 70%, and the operator can work continuously without fatigue. A button control enables the percussion movement to be stopped or started at will.

Of the two models available, type ZL8 weighs 3·3 lb, operates at speeds of 630 and 1900 rpm, and has a drilling capacity in steel of $\frac{5}{16}$ in., in wood $\frac{1}{2}$ in., and in stone (with percussion head) $\frac{1}{4}$ in. The larger model, type ZL13, weighs 6 lb, operates at 560 and 1440 rpm, and has corresponding drilling capacities of $\frac{1}{2}$ in., $\frac{3}{4}$ in., and $\frac{5}{8}$ in. respectively.

Motor Control and Alarm Units

Specially designed motor control and alarm switches are used in the new Oil Gasification Plant under erection at the Billingham Division of Imperial Chemical Industries Limited. In this plant, the many motor drives used are started by contactors mounted in a special switch-room, and local control of the motors is achieved by units in special weatherproof cases which house terminal blocks for incoming leads, an ammeter, and two " sparkless switches ", specially designed by I.C.I., these swtiches being used in place of normal push-buttons to operate the contactors in the switch-room. Cable entry is via a detachable gland-plate in the base of the unit, and connection is facilitated by a removable inspection cover on the front of the unit and in direct line with the terminal block.

Motor control and alarm units, all of which are manufactured by Westool Ltd., of St. Helen's Auckland, to the basic I.C.I. circuit design, are also mounted on the plant control panels in the central control room. These units provide a stop-button and also give immediate indication of the failure of any drive, a green lamp being illuminated when the circuit is normal and a red lamp when any fault develops. The red lamp can be de-energized by pressing a stop/reset button. The chassis for each unit slides into a case which is fixed to the main control panel, as shown in the illustration, connections being made by a 12-way plug and socket. The socket, which is on the chassis, is automatically aligned with the plug in the case by means of pins which mate with holes in advance of the plug and socket connection. As there are six variations of these units, they are fitted with non-interchangeability pins to prevent units being inserted incorrectly.



The plant is provided with a large number of measuring instruments to control and check its operation. If these instruments show that something is wrong, they operate alarm units, each of which is designed to light a " fault " lamp on the main control panel and to operate a buzzer. When an instrument detects a fault, a contact opens, causing the fault lamp to flash and a buzzer to sound. A " cancel-alarm " button on the main control panel enables the operator to stop the buzzer and causes the fault lamp to glow continuously. When the failure has been corrected, the circuit returns to normal and the lamp is extinguished. The alarm units are fitted into dust-proof cubicles housing 9, 15, 24, 33, or 36 units. The cubicles are split into sections, each containing a tier of three units, hinged at the bottom for easy inspection and maintenance.

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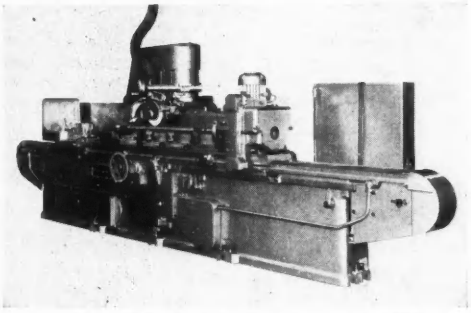
SPLINE-GRINDING MACHINE

With a capacity of 72 in. between centres, the new 72-in. spline-grinding machine announced by A. A. Jones & Shipman Ltd., of Leicester, is capable of grinding down to zero work diameter with a wheel worn to 7 in. diameter, or 13 in. work diameter with a new 10-in. diameter wheel. The working stroke is 84 in., of which 66½ in. is useful grinding length, the remainder being occupied in " run-out " over the tailstock to the two truing positions. The centre height of the machine (work-head centre to table top) is 7 in., and the range of vertical adjustment of the wheelhead, measured between the wheel-spindle centre-line and the work centre-line, is from 3½ to 11½ in.

The wheelhead support column has no cross traverse, the necessary diamond positioning for side-arc truing of the wheel being obtained from movement of the truing arrangement mounted on the table. The wheelhead has a long slide, fitted with square gibs. Three taper-adjusting strips are provided at each extremity of the wheelhead slide, ensuring a snug fit in both planes of the wheelhead to the wheelhead slide. The wheelhead is vertically adjustable by means of a handwheel working through a worm-wheel and screw. The complete feeding system, including the feed screw, is entirely submerged in an oil bath. The wheelhead-feed handwheel gives 0·050 in./rev. feed, with an additional fine-feed arrangement graduated in, and capable of moving the wheelhead by, increments of 0·0001 in. Balance chains lead from the top of the wheelhead over ball-bearing pulleys at the top of the wheelhead column, the balance chains being attached to a long cylindrical balance weight.



The wheel-spindle housing is a demountable unit, and the wheel spindle can be moved over a range of ½ in. in the direction of its axis, and through its own bearings, by moving the complete thrust arrangement, using taper-wedge methods controlled by a thumb-wheel on top of the wheel-spindle. Axial movements of the wheel-spindle can be registered on a dial indicator, the whole arrangement providing a fine side-feed motion, which, owing to the fact that the sliding member is itself the wheel spindle, gives adequate sensitivity.

The indexing workhead is hydraulically operated from its own self-contained unit, but is electrically signalled into and out of action. The accuracy of indexing is dependent solely on a notched plate, a pivoting indexing pawl being kept in contact with one face of the notch, both by a spring-loaded plunger and by hydraulic torque. The maximum number of notches catered for as standard is 48. One index plate having 48 notches, with masking plates to give 2, 3, 4, 6, 8, 12, 16, and 24 divisions, is provided with the machine. To change the indexing sequence it is necessary to change only the index and/or masking plates.

The truing arrangements have enclosed sliding members, and provision is made for securing a cross traverse having a range of approximately 3 in. each side of centre, in order to produce side-truing effects. Hydraulic power supply for the main table is derived from an external oil tank. Electrical arrangements are not built into the machine, but are contained in a cabinet, floor-mounted, alongside the supply tank.

The major hand control is a combined " stop-start ", speed control, and hand traverse-engagement lever. This is a lever having a " joy-stick " movement in that it is capable of a short movement towards and away from the operator, this movement taking place in a gate. In the " off " position the lever is spring-loaded to the rear of the gate, away from the operator. From this position, the lever can be rotated anticlockwise, and this has the effect of engaging a hand traverse mechanism which must be disengaged by returning the lever to the centre position before power movement of the table can be engaged, thus forming an inter-lock. The maximum table speed is 60 fpm. With the lever again at the central position it can be pulled slightly towards the operator. This movement applies full working pressure to the system and positions the lever in the gate so that it can now be moved in a clockwise direction. The table will then move at a speed depending upon the extent to which the lever is rotated clockwise. A stop is provided, so that the same traverse speed can be engaged repetitively. To stop the machine, the level is centralized. From this centre position either the hand traverse or the power traverse may be engaged. The reversing lever is also " joy-stick " mounted.

NEW CONCEPT IN MAGNETIC MEMORY DEVICES

A new concept in memory devices, designated the " Twistor ", is announced by the Bell Telephone Laboratories, of New York, and is expected to make possible the construction of memory systems which are simpler and more economical to fabricate than existing systems. It is believed that this concept may have extensive applications in computers and electronic switching systems requiring the use of rapid-access, high-capacity memories.

The Twistor concept paves the way for the construction of magnetic memory arrays by merely interweaving horizontal copper wires and vertical magnetic wires. Such a device would be similar to a ferrite-core array, without the cores, and would operate in much the same manner. The new device gets its name from a characteristic of wire made of magnetic material, i.e., that torsion applied to such a wire shifts the preferred direction of magnetization from a longitudinal to a helical path. The coincidence of a circular and a longitudinal magnetic field can then be used to insert information into this wire in the form of a polarized helical magnetization, and the magnetic wire itself can be used as a sensing means. Application of torsion to the magnetic wire in a final device may be unnecessary, as the helical path for the preferred direction of magnetization can perhaps be " frozen " into the wire during processing.

In practice, the circular magnetic field is provided by a current pulse through the magnetic wire, and the longitudinal field by a current pulse through the copper wire perpendicular to the magnetic wire. Thus, storage requires two coincident current pulses, one pulse by itself being insufficient. Read-out is accomplished by overdriving the longitudinal field in the reverse direction, the read-out signal being sensed across the magnetic wire. Because the lines of magnetic flux along the helical

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path wrap the magnetic conductor many times, a favourable increase in the output signal is obtained.

Investigations are now under way to determine the optimum size and composition of the magnetic wires. It appears that a conductor plated with magnetic material may have some advantages, and diameters as small as 0·001 in. appear to be feasible. At least 10 bits of information per inch may be stored on such a wire without adverse interaction.

In conventional magnetic-core memory devices, conductors must be threaded through the cores to make up a suitable matrix. When a ferrite sheet is employed, either a threading or a plating operation is necessary to locate the conductors suitably. However, with the Twistor, the ferrite material is completely eliminated and no threading or plating is necessary. The speed of operation and output of the Twistor is comparable with that of ferrite memory systems. Present indications are that the drive circuits for a Twistor array can be readily transistorized. Thus, a memory system using the Twistor concept will retain all of the advantages of ferrite core or sheet systems, and will be much simpler and more economical to fabricate.

MINIATURE UNIVERSAL METER FOR ELECTRICAL MEASUREMENTS

Stated to be the first of its type, the AVO " Multiminor " pocket-sized current, voltage, and resistance meter, announced by AVO Ltd., of London, S.W.1, combines exceptional accuracy with durability, despite the fact that it is mass-produced and marketed at a very competitive price. Two models are available, i.e., for use in temperate climates or under adverse climatic conditions. For the pan-climatic version, a special fungus-resistant moulding powder is used, providing a very high factor of electrical insulation, even under conditions of extreme humidity. Furthermore, the indicating movement is housed in a dust-proof casing and all wiring is termite-proof.

The most outstanding feature of the instrument is the use of printed resistors, produced from a special metallic alloy, this being the first time that such resistors have been used on any mass-produced apparatus. In one instance, it has been possible to combine a printed resistor with an auxiliary switch-plate as an integral part of the selector-switch mechanism, another printed resistor forming the universal meter shunt. High-stability carbon resistors have also been employed, wherever necessary.

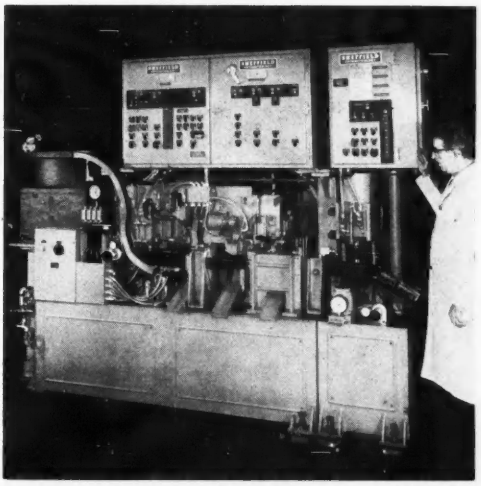
Another interesting feature is the provision of a high-quality rotary selector switch (usually the weakest component in inexpensive multi-range meters, if fitted at all). This switch is of unique design, a series of eighteen fixed silver-plated contacts being rigidly held in a ring of high-grade moulding material and wiped by a double-contact rotor arm.

Measuring only $5\frac{5}{8} \times 3\frac{5}{8} \times 1\frac{3}{8}$ in., the instrument has a total of nineteen ranges, i.e., seven for d.c. voltage measurements up to 1000 V, five for a.c. voltage up to 1000 V, five for d.c. current up to 1 A, and two for resistance up to 2 megohms. A single large scale is provided for current and voltage measurements and another scale for resistance measurements. Only two connection sockets are used for all measurements.

AUTOMATIC TAPER ROLLER BEARING ASSEMBLY MACHINE

Developed by the Sheffield Corporation, of Dayton, Ohio, a new automatic taper roller bearing assembly machine gauges the diameter and flange thickness of the inner race, selects the proper roller size, and assembles these, together with a cage. It then further gauges the assembly for torque and " stand-out " before segregating, rated production being about 1000 bearing assemblies per hour.

The inner race is fed into the first gauge station at the left-hand side of the machine, where it is inspected for diameter and flange thickness to determine the correct roller size to be assembled within a given ring. Rollers are selected from one of six preselected-size hoppers, which are located behind the machine, and the correct number and size are fed into assembly position at an assembly station. During transfer from the gauging to the assembly station, a roller cage is fed into position from a vibrating hopper at the left side of the machine.



At the assembly station, the rollers are inserted into the cage and the inner-race ring inserted into the roller-cage combination. The assemblies are then transferred to additional stations, where they are inspected for the correct number of rollers and where the cages are crimped to make permanent assemblies. The last station inspects the assembly for correct stand-out under a revolving load condition, after which they are segregated into " acceptable " or " reject " chutes.

LIQUID-RETAINING SYNTHETIC MATERIAL

Development of a basic new synthetic material capable of containing and retaining liquid during manufacture and then giving it off at a predetermined rate, is announced by Perma Industries, Inc., of Los Angeles, California. In addition, if manufactured in sheet form, without liquid as an inherent ingredient, it becomes a fabric which combines waterproofiing characterstics with porosity, permitting the controlled passage of air.

Designated " Porelon ", the new material is completely reticulated and microporous, consisting essentially of microscopic spheres of resin, each of which is approximately 6 microns in diameter. In the manufacturing process millions of these spheres are dispersed into a mixture consisting of a bonding agent and a liquid. The liquid may be ink, perfume, a medication, a lubricant, or any other which is miscible with the bonding agent. As heat is applied, the bonding agent is absorbed into the microscopic spheres. At a certain temperature these spheres become bonded together at their points of contact, creating a reticulated or interconnecting pore structure. As the spheres are fused together, the liquid ingredient, formerly mixed with the bonding agent, is trapped in this maze of pores, which are comparable in size with some of the larger molecules, such as those making up starch. Because of the microscopic size of the spheres, and still smaller size of the pores, the liquid is held within the material by capillary attraction. This attraction also keeps the liquid evenly diffused throughout the material. As liquid is taken off the surface of the Porelon, it quickly and evenly replaces itself as the

dynamic technique

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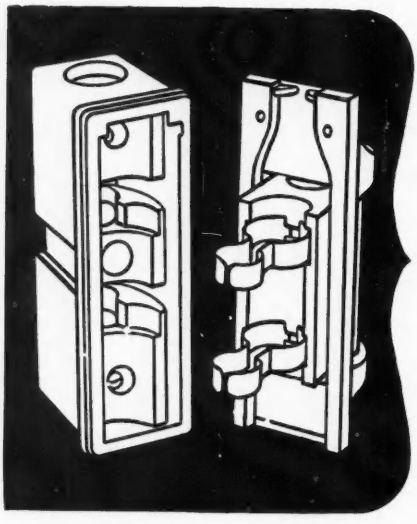

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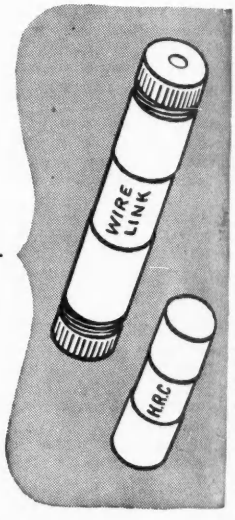

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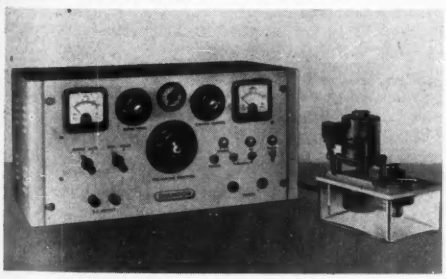
remaining liquid redistributes itself throughout the mass by capillary attraction.

Porelon can be manufactured to contain 40% or more liquid by weight. Thus, a rubber stamp, made from a strip of Porelon only $\frac{3}{16}$ in. thick, has been shown to contain sufficient ink to yield no less than 60,000 clear impressions. In addition, as it can be manufactured in any colour by the addition of dyes or pigments and with any desired degree of resiliency, from soft and sponge-like to rigid, an extremely wide range of other applications is possible. Thus, for instance, it can be used for self-lubricating bearings, as it can be produced to contain many lubricants, including silicones ; also, it can be cast in any shape for use as a self-lubricating bushing or washer, or as a lubrication wick. Similarly, small pieces of Porelon can be placed inside delicate, enclosed instruments, so that vapour given off will keep the instrument lubricated and free from rust.

Other possible applications under investigation include the use of blocks of Porelon containing dissimilar electrolytes for use as a wet-cell battery, uses in medical fields, e.g., self-medicating bandages and plasters, and uses in the manufacture of cosmetics, e.g., as a combined lipstick container and applicator, in which the tip retains its shape permanently, or as a container and applicator for perfumes, deodorants, etc. Similarly, in the agricultural field, it can be made to emit vapours for the prevention of fungus growths on citrus fruits and vegetables or as a container for insecticides. Another interesting possibility is its use as a filtering medium for liquids. In this case the Porelon is produced without a liquid ingredient, and the size of the pores is controlled, as required, during the manufacturing process.

ELECTROLYTIC POLISHER WITH CONTINUOUSLY ROTATING LIQUID COLUMN

Based on apparatus developed by the Atomic Energy Research Establishment, Harwell, the Shandon electrolytic polisher, manufactured by the Shandon Scientific Company Ltd., of London, S.W.7, is characterized by its unique method of dispersing the anodic layer, resulting in complete freedom from flow lines, particularly in multiphase alloys. This is achieved by pumping the electrolyte through a series of orifices in such a way that it contacts the specimen in the form of a continuously rotating and renewed vertical liquid column. As a result, cold working and false deformation structures are eliminated, and specimen preparation is reduced to a mere routine, instead of a highly skilled operation.

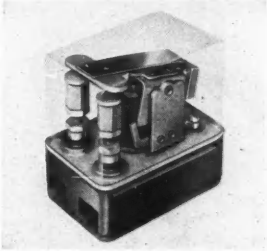


The polishing deck, mounted on rigid PVC, is a self-contained unit, which rests on the electrolyte tank and contains the pump, specimen clamp, and electrolytic cell. The pump is made from PVC and polythene, and all components in contact with the electrolyte are constructed of corrosion-resistant material. The specimen, forming the anode, is securely held in position by a spring-loaded specimen clamp, which serves at the same time to make the necessary electrical connection for the specimen.

The specially designed power supply has separate d.c. outputs and controls for manual and automatic polishing and etching. Additional output terminals provide facilities for beaker etching, when required. For manual operation, all switches are independently and separately controlled by on/off switches. For automatic operation, a time-switch is set to the required polishing period (from 1 to 90 sec), and at the end of the period both the pump and the direct current are automatically switched off. Electrolytic etching can be carried out as part of the operation by switching to the " etch " position during the last seconds of the cycle.

RELAYS FOR AIRCRAFT APPLICATIONS

To meet the constantly changing and stringent specifications of the aircraft industry, a new range of aircraft relays has been developed by The Plessey Co. Ltd., of Ilford, Essex. Of these, the 60-A bridging make-relay illustrated, which is built to withstand severe conditions of shock, vibration, humidity, and altitude, operates over an ambient-temperature range of −65°C to +70°C and is available in two forms, i.e., hermetically sealed or dust-proof, both fitted with identical mechanisms.



Compact, robust, and reliable, this relay has a balanced armature, so that correct operation is not affected by vibration or acceleration. In addition, the bridging contacts have a wiping action, thereby minimizing contact resistance. The hermetically sealed model, which is flame-proof, weighs $10\frac{1}{2}$ oz and has a moulded terminal shroud and detachable terminal cover, while the dust-proof model, weighing $9\frac{1}{2}$ oz, has terminals which are accessible by removal of the dust cover.

The overload capacity of both versions, which are wound for 28 V d.c., is 480 A d.c. at 60,000 ft, or 600 A d.c. at lower altitudes, non-inductive. The hermetically sealed model does not depend on the perfection of sealing, for this overload capacity. At normal rated current, subject to certain limitations regarding the inductive nature of the controlled circuit, these relays are capable of a minimum of 100,000 make-and-break operations.

Surface Rolling as a Method of Increasing the Fatique Strength of Gears

(*Concluded from page 578*)

complex shape), coupled with induction hardening of the tooth flanks.

This investigation has established that gears of cast steel are by no means weaker than forged gears of similar core hardness, insofar as fatigue strength is concerned. Indeed, tests on segments of actual production gears have demonstrated that the application of surface rolling achieves a fatigue life in cast gears which is even higher than that of forged gears.

As a result of these investigations, this process of surface rolling of tooth spaces was introduced into the batch production of gears. So far, experience available on the operation of a diesel-electric locomotive which has travelled 150,000 km using these gears has confirmed the effectiveness of this method of work-hardening.

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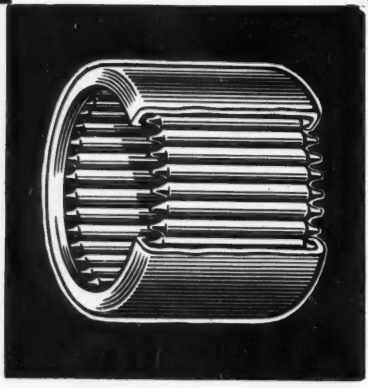

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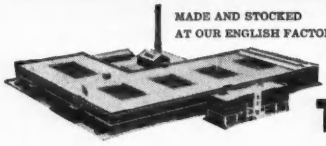

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NEWS OF THE MONTH

PERSONAL

Mr. F. Baxter has been appointed home sales manager for machine tools with A.A. Jones & Shipman Ltd., Leicester.

Mr. Miles Beevor, formerly managing director and deputy chairman of the Brush Group, has joined the Board of Rubery, Owen & Co. Ltd., Kent House, Market Place, London, W.1.

Mr. J. Calderwood, M.Sc. (Marine Eng.), technical director of Associated British Oil Engines Limited, has been appointed an executive director of the Board of The Brush Group Ltd. **Mr. Maurice Tattersfield, A.C.A., F.C.C.S.,** hitherto managing director of Brush Electrical Engineering Co. Ltd., Loughborough, is relinquishing these responsibilities and has been appointed an executive director of The Brush Group Ltd. and remains a non-executive director of Brush Electrical Engineering Co Ltd. **Mr. B. L. Goodlet, O.B.E., M.A., M.I.C.E., M.I.Mech.E., M.I.E.E.,** director and chief engineer, Brush Electrical Engineering Co. Ltd., Loughborough has been appointed managing director of that company. **Mr. R. G. Hooker,** director and general works manager, Brush Electrical Engineering Co. Ltd., Loughborough, has been appointed director and general manager of that company.

Mr. J. Chapman has been appointed director and general manager of Horstman Ltd., Bath, one of the Simms Group of Companies. **Mr. M. A. Hassid,** managing director of Motor & Electronics Corporation, which has recently been acquired by Simms, has been elected to the Board of Simms Motor Units Ltd., Oak Lane, London, N.2, and to other Simms companies, including Horstman.

Rear Admiral J. E. Cooke, C.B., M.I.Mech.E., formerly engineer-manager of H.M. Dockyard, Portsmouth, who retired from the Royal Navy last July, has joined Vokes Ltd., Henley Park, Guildford, Surrey, in the capacity of consultant.

Mr. B. W. A. Dickson, C.B.E., has been elected chairman of Oliver Pell Control Ltd., in succession to **Mr. R. Sefton-Turner,** who died on October 24th. Mr. Dickson, who was director and general manager of the Aircraft Division of the Vickers Group of Companies, is now a director of Alltools Ltd., Flight Refuelling Ltd., Flight Refuelling (Holdings) Ltd. and Prodorite Ltd.

Mr. N. J. Ellerbeck has been appointed commercial manager of Simms Motor Units Ltd., Oak Lane, London N.2, to succeed **Mr. W. Newland,** who has been appointed export manager and assistant to the general manager, **Mr. J. Ayres. Mr. W. H. Binns** and **Mr. D. H. Henri** have been appointed sales managers of the Operators and Manufacturers Divisions, respectively.

Mr. Brian Arthur Gomm has been appointed general manager of F. Perkins (S.A.) (Pty) Ltd., Johannesburg, the South African subsidiary of the Peterborough diesel engine company.

Mr. J. M. Hallett, publicity manager of Ferranti Ltd., Hollinwood, Lancs, has been elected to the publicity committee of BEAMA.

Mr. Fred Hamer, chief engineer, and **Mr. Ansill H. Smith,** works superintendent, have been appointed directors of Ashworth & Parker Ltd., Riverside Works, Bury, Lancs.

Mr. T. S. Kilpatrick has been appointed director and general manager of Workington Iron and Steel Company, a branch of The United Steel Companies Ltd., in succession to **Mr. Langton Highton, J.P.,** who relinquished his position after 47 years' service, but will continue on the Board of United Steel and its associated companies in Cumberland. **Mr. T. Sanderson** has been appointed general works manager, in succession to **Mr. D. R. Wattleworth, O.B.E.,** who retired after 50 years' service.

Mr. P. J. Landon, M.I.Ex., has been appointed sales manager of the newly formed Engineering Division of Airtech Ltd., Haddenham, Bucks.

Mr. R. G. Lewis, formerly general amanager of Birwelco Ltd. and Brown Fintube (Great Britain) Ltd., Chester Street, Aston, Birmingham, and a director of Petrochem G.m.b.H., Dortmund, Germany, and of Servotomic Ltd., 175 Piccadilly, London, W.1, has now been appointed director and general manager of the two former companies.

Mr. S. Mackenzie-Owen, M.B.E., has been appointed manager of Acheson Colloiden N.V., Scheemda, Netherlands, the Dutch company of Acheson Industries (Europe) Ltd., 18 Pall Mall, London, S.W.1.

Professor W. E. Morath, D.Sc., a scientist of international repute in the field of forest products technology and wood anatomy, has joined the Board of International Plastics Ltd., 3 Vere Street, London, W.1, as director of research and development.

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Mr. A. E. Parritt has been appointed contracts engineering manager, and **Mr. D. Phelps,** manager of the application engineering department, of Foxboro-Yoxall Ltd., Lombard Road, Merton, London, S.W.19.

Mr. A. Phillips has been appointed Midland area manager of Monks & Crane Ltd., Garretts Green Lane, Birmingham.

Mr. H. P. Potts, M.I.Mech.E., director of the Birmingham Small Arms Co. Ltd., chairman of B.S.A. Guns Ltd. and of Monochrome Ltd. and managing director of the B.S.A. Tools Group of Companies, has joined the Board of The Colchester Machinery Corporation Ltd., Canada, which is associated with the Colchester Lathe Co. Ltd., Colchester, Essex. Both are members of the 600 Group of Companies. Mr. Potts is immediate Past President of The Machine Tool Trades Association and member of the European Committee for the Co-operation of the Machine Tool Industries.

Mr. P. M. Thomas, D.S.O., T.D., B.A. (Cantab.) formerly joint managing director, has been appointed sole managing director of William Beardmore & Co. Ltd. **Captain Q.H. Paterson, D.S.O., R.N., M.I.Mech.E.,** has resigned his joint managing directorship, but will remain on the Board in executive capacity.

Air Commodore Sir Arthur Vere Harvey, C.B.E., M.P., has been elected chairman of Aero Research Ltd., Duxford, Cambridge, and of Ciba Ltd., Horsham, in succession to **Sir Raymond Needham, Q.C.,** who remains a director of both companies. Sir Arthur is deputy chairman of Handley Page Ltd. and a director of Mullard Ltd. and Philips Electrical Ltd.

Dr. K. J. Wootton, A.M.I.Mech.E., has been appointed deputy manager of the Atomic Energy Division of The General Electric Co. Ltd., Erith, Kent.

BRITISH STANDARDS

(*Copies of British Standards may be obtained from the British Standards Institution, 2 Park Street, London, W.1*)

Safety Colours in the Factory. A new attack on industrial accidents is heralded by the publication today of the British Standards Institution's recommendations on *Safety Colours in Industry* (B.S.2929).

The purpose of these recommendations is to establish throughout industry the use of a universal system of colours for the identification of hazards and safety equipment.

As these recommendations are applied in factories, mines, shunting yards and other industrial installations, the confusion which now exists through the use of a variety of different colour codes should gradually be removed. The main advantage will be to associate in the minds of work-people certain colours and signs with particular types of hazard, an association of ideas which will not be upset should workers move to a different department in the same works or to a completely different factory or site.

Indeed, the new system has a greater significance in that it is in substantial agreement with the code of safety colours shortly to be recommended for world-wide adoption by the International Organization for Standardization. This international code, as it is taken up by other states, should help to safeguard workers moving from one country to another by establishing a universal and easily-recognized safety-colour system.

The new British Standard recommendations are extremely simple. The colours are : red, orange-yellow and green. (Advice is given in the standard on the selection of the right shades of these colours.)

Red has the meaning STOP.

Orange-yellow means WARNING OF DANGER.

Green is used to identify or locate safety equipment and safety routes.

Contrasting colours are used with the three main colours to form patterns which make for easier visibility. Thus a red and white chequered pattern would be used for the door of a store containing petroleum spirit.

Geometrical forms—a circle, triangle, or rectangle—may be used as part of a safety message, but the colour in which they are painted and their meaning will always be the same. A circle, for instance, is to be carried out in red (or red and white) and implies an order of some kind.

Examples of the application of the standard safety colours are :

RED for buttons, handles or wires to be used in an emergency to stop a machine ; also for fire-fighting equipment.

RED AND WHITE CHEQUERED PATTERN to indicate barricades and obstructions.

ORANGE-YELLOW WITH BLACK DIAGONAL STRIPES to give warning of risks arising from changes in floor level, floor and head obstructions and open machinery guards.

GREEN for fire and emergency exits.

The standard contains illustrations in colour of typical applications.

A green cross, in place of the familiar red one, is recommended for use on first-aid cabinets and so forth. This break with tradition was agreed on by the Committee —widely representive of industry—which drafted the standard, for these reasons : the green cross symbol is in line with the international code referred to above ; and green is already clearly associated in the public mind with safety, while red carries the meaning " stop—keep away ! " Price of the Standard is 4*s.* 6*d.*

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BUSINESS NOTES

Rose, Downs & Thompson Ltd., Old Foundry, Hull, have acquired the licence from Hch. Bertrams A. G., Basle, Switzerland, for the manufacture and supply of high temperature heating plants using the Bertrams system, within the British Commonwealth, Dominions and Colonies and Ireland. The Bertrams plant incorporates interesting developments in both the liquid and vapour phases, which have raised the efficiency of the boiler installation to about 80%.

B. T. R. Industries Ltd., Herga House, Vincent Square, London, S.W.1, announce the formation of a Group Aero Division, which will concentrate on the design and manufacture of components, such as wheel and brake assemblies, hydraulic and pneumatic control equipment, high and low pressure hose units for fuel systems and other specialised rubber and plastic products. Further expansion, particularly into the field of components for guided missiles, will be accelerated. Mr. C. G. Erlam, who has extensive experience in the aircraft industry, has been appointed manager of the new Division.

The Free Piston Engine Co. Ltd. have removed their head office and their considerably expanded research and development division to Mackay Works, Faggs Road, Feltham, Middx.

Rotary Hoes Ltd. announce that a new drawing office block, experimental workshops and storage sheds have now been completed at their new factory premises at West Horndon, Essex.

Hordern Richmond Ltd., Haddenham, Bucks, has shown to more than 80 guests at the British Council Film Theatre, London, a 40-minute film, describing the manufacture of " Hydulignum " densified wood laminates and its various applications for press tools, propeller blades and many other purposes. Sir Norman Kipping, chairman of the Federation of British Industries, was amongst the guests at the premiere of the film, showings of which will be arranged in major industrial centres at home and overseas.

Hoover Ltd. have recently almost doubled in size the engineering department at their headquarters at Perivale, Middlesex, which now occupies some 25,000 square feet. In addition, there are further laboratories in the company's other factories at Merthyr Tydfil, Cambuslang and High Wycombe. The engineering department comprises design and development laboratories, drawing office, model shop for prototype manufacture, products control laboratories and a department concerned with fundamental research into possibilities for new and revolutionary products.

The Pyrene Co. Ltd., 9 Grosvenor Gardens, London, S.W.1, have acquired additional patents, trade marks, sales and manufacturing rights hitherto owned by the American Pyrene company. The British company is thus enabled to develop export markets in European countries and in South and Central America. Controlling interests of the Pyrene Company include Minimax Ltd., High Pressure Components Ltd. and Sun Engineering (Richmond) Ltd. Mr. Francis Harrison is chairman of the company.

Atomic Industrial Forum, Inc., 3 East 54th Street, New York 22, N.Y., announce the availability of a complete conference catalogue and of all papers from sessions of its recent conference on " The 1957 Nuclear Industry ".

Westool Ltd., St. Helen's Auckland, Co. Durham, announce that, in anticipation of greatly increased demand at home and overseas, the production of " Westair " climatizers is now being concentrated and expanded in a separate factory. A wide range of models is being produced for use both in tropical and temperate climates.

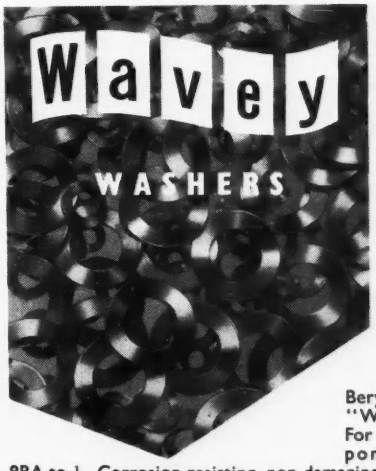
Broadway Equipment Ltd., 194–196 Finchley Road, London, N.W.3, have been appointed by E. Gibas, Amsterdam, Holland, sole agents in the United Kingdom for the sale of their fully automatic tube grinding and polishing plant and their trimming machines for non-cylindrical drawn shells.

The Electrical Engineers Exhibition to be held at Earls Court, will be opened on March 25th, 1958, by the Rt. Hon. Sir David Eccles, K.C.V.O., M.P., President of the Board of Trade. The Exhibition will cover an area of 450,000 square feet.

Caterpillar Co. Ltd., 55 St. James's Street, London, S.W.1, announce a five-year modernisation and development programme at Great North Road, Newcastle upon Tyne, the site of the old Birtley works. An area of 400,000 square feet of manufacturing space, in addition to office blocks and warehouses, will be developed. Col. R. T. Edwards, who was previously managing director of The Birtley Co. Ltd., is director and manager of operations at Caterpillar's Newcastle plant.

English Steel Tool Corporation Ltd., Openshaw, Manchester, have recently opened new premises at 167 Dukes Road, London, W.3. Tel. No. : ACOrn 5602–3.

The Du Pont Company (United Kingdom) Ltd., a wholly owned subsidiary of E.I. Du Pont de Nemours &



Beryllium Copper "Wavey" Washers. For Electronic Components. Range 8BA to ½. Corrosion resisting, non-damaging to components, higher resistance of "set", higher recovery of load, permanent spring action. They are fabricated from Beryllium copper, heat treated to VPN 350 minimum, Electro Plated to DTD.924, Cadmium Plated to DTD.904 and Passivated to DTD.923. Samples and price lists on request.

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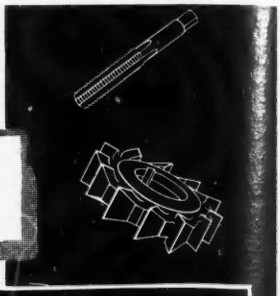

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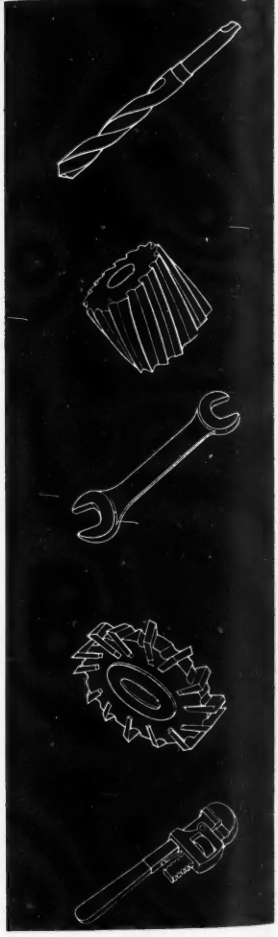
SUMMIT — Joseph Thompson (Sheffield) Ltd
SUPER SPEED — Slack Sellars & Co Ltd
Wolf — Electric Tools Ltd



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Sales managers for the Hand Tool Division of the Bren Manufacturing Company

JW.Ad 4054

Co., Inc., with offices at 5 Charles II Street, London, S.W.1, has been formed to manufacture and sell Neoprene in the United Kingdom and European markets. Durham Raw Materials Ltd. will act as sales agents.

J. M. Steel & Co. Ltd., Kern House, 36–38 Kingsway, London, W.C.2, have opened new offices at 144 St. Vincent Street, Glasgow, C.2. Tel. No.: 3262/3.

C. H. Johnson (Machinery) Ltd., Adswood, Stockport, have been appointed sole agents in Great Britain and Northern Ireland to manufacture under licence a Swiss designed industrial lifting platform with some interesting features. Of simple electro-mechanical design, it is already used extensively throughout Europe for a variety of lifting and loading purposes.

Ketay Limited, Romford, Essex, in conjunction with Norden-Ketay Corporation in the United States, has recently concluded a licensing agreement with the Societe Anonyme Precilec of France.

This agreement provides for the manufacture under licence, and sale, of Ketay and Norden-Ketay synchro- and servo-mechanisms in France, together with the interchange of technical and manufacturing information between the three companies.

The Instruments, Electronics & Automation Exhibition will be held at Olympia, London in April, 1958. With more than 60 new exhibitors, the British Section is completely sold out.

In the Overseas Section of the Exhitition stand space has been booked by exhibitors from Belgium, Denmark, France, Germany, Holland, Sweden, Switzerland and the U.S.A.

In addition to the trade associations who sponsored the 1957 I.E.A. Exhibition—The British Electrical and Allied Manufacturers' Association, The British Industrial Measuring and Control Apparatus Manufacturers' Association, the British Lampblown Scientific Glassware Manufacturers' Association, The Drawing Office Material Manufacturers' and Dealers' Association, the Scientific Instrument Manufacturers' Association of Great Britain—the Radio Communication and Electronic Engineering Association has joined this impressive list in promoting the 1958 Exhibition.

I.E.A. 1958 will again be accompanied by a Conference, taking place at Olympia at the same time as the Exhibition itself. This year's Conference will be international in character, and scientists, engineers and industrialists from many Continental countries, Canada and the U.S.A. have already asked for details.

The exhibition is again organised on behalf of the promoting trade associations by Industrial Exhibitions Limited, 9 Argyll Street, London, W.1.

The American Welding Society will hold its annual Welding Show at Kiel Auditorium, St. Louis, 15th to 17th April, inclusive. During the same week, 14th-18th April, inclusive, the society will hold its annual technical meeting at the Hotel Statler. An informal Welding Conference, on a less technical basis, also will be conducted. Plant tours in the St. Louis area will round out the programme.

Information may be obtained by writing to the A.W.S. Welding Show, c/o Robert T. Kenworthy, exposition management, 12 East 41 Street, New York 17, N.Y.

CONTRACTS

The Nuclear Power Plant Company Ltd. have received from Ing. Mattei, President of Ente Nazionale Idrocarburi, Rome, a letter of intent to negotiate the construction of Nuclear Power stations in Italy, and also to conclude a long term agreement for mutual co-operation on the design and development of power reactors. The agreement will be made between N.P.P.C. and AGIP Nucleare, a subsidiary of E.N.I. and will refer to reactors of the gas-cooled type.

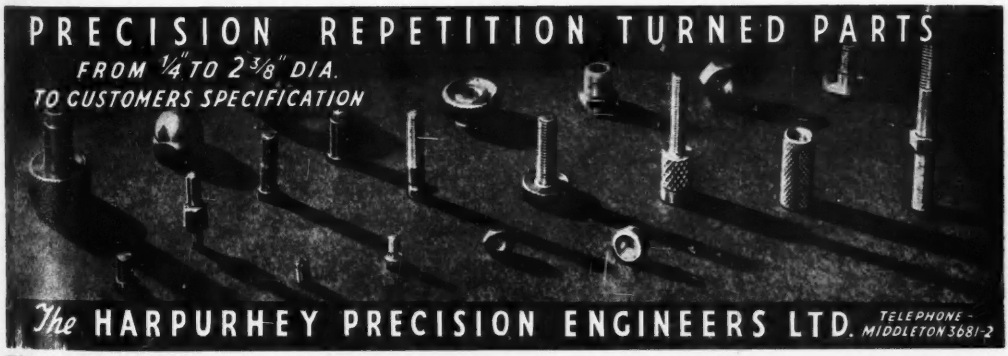
Throughout the negotiations, both parties have had the co-operation of the United Kingdom Atomic Energy Authority and their staff.

The first station to be constructed under this arrangement will have an output of 200 megawatts and will involve the manufacture in the United Kingdom of considerable quantities of plant. The Nuclear Power Plant Company will be responsible for the overall design and satisfactory commissioning of the station, while AGIP Nucleare will place all local contracts and will carry out the site erection.

The Nuclear Power Plant Company is a consortium consisting of the following companies : C. A. Parsons & Co. Ltd., A. Reyrolle & Co. Ltd., Head Wrightson & Co. Ltd., Sir Robert McAlpine & Sons Ltd., Whessoe Ltd., Strachan & Henshaw Ltd., Alex Findlay & Co. Ltd., Clarke, Chapman & Co. Ltd. The Chairman is Sir Claude D. Gibb, K.B.E., F.R.S.

The company is already engaged on the construction of a power station at Bradwell-on-Sea, Essex, which will have two reactors, each with a guaranteed output of 150 megawatts. The single reactor for the Italian station will be of the same over-all dimensions as the Bradwell reactors, and the increase in output reflects the research and development that has taken place since the Bradwell design was accepted a year ago.

National Free Piston Power Limited, newly formed company of the Brush Group, announce that they are to receive a contract from the Zinc Corporation Limited covering the supply of a free-piston turbo-air compressor plant for installation at Broken Hill, Australia. The plant will consist of three National GS.34 free-piston gasifyers,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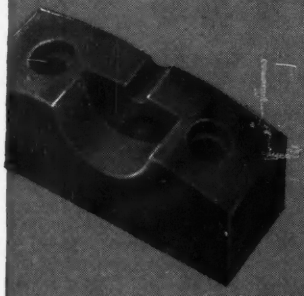

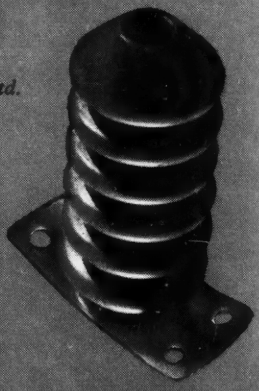

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Intensive research at the I.C.I. Nobel Division laboratories is constantly providing new knowledge on all aspects of silicones. This information is freely available to intending users—Technical Service experts will be pleased to give advice on any new or existing applications.

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MM 49

one Brush (series 200) expansion gas turbine, direct coupled to an Oerlikon rotary air compressor.

The contract, which is subject only to Australian import regulations, will be supervised on behalf of the Zinc Corporation by Rubert Bruce and Sons.

The Brush Group is to supply three large diesel electric generating sets for a Power Station in French Guinea, to be built by an international group of aluminium companies at Fria, French Guinea.

The Brush Group obtained this contract in the face of international competition, and were able to give very quick deliveries for the equipment.

Each set will generate 2,200 kW A.C., 5,500 at 428 rpm and will consist of a Mirrlees 3,150 bhp engine directly coupled to a Brush alternator.

Ferranti Ltd. have been awarded a contract valued at $3,925,250 by the Power Authority of the State of New York for thirteen generator transformers.

The contract covers six 180,000kVA, 13·2/240kV 3 phase transformers and seven 180,000kVA 13·2/120kV 3 phase transformers for the Lewiston Power Station of the Niagara Power Project.

The transformers will be of the forced-oil, forced-water cooled, inert gas-filled type and each will be directly coupled to a 167,000kVA 3-phase generator. The transformers will each weigh approximately 183 tons (240kV) and 155 tons (120kV). Delivery is to commence in the middle of 1959 and be completed by the end of 1960.

This contract is believed to be the largest one for transformers so far placed in Britain by the U.S.A. It brings the total number of transformers supplied, or under construction by Ferranti Ltd. for the U.S.A. to 75 of a total capacity of nearly 5,000,000kVA and a value of almost $10,000,000.

Prince-Smith and Stells Ltd., Yorkshire specialists in worsted machinery and members of the Platt Brothers Group, have secured an order from Finland for a " New Bradford " system mill plant, value £250,000. The system incorporates Raper Autolevelling and high-draft spinning.

This contract is attributed to the Company's exhibit at the recent Helsinki Fair.

The award of a £1½-million contract to **Constructors John Brown Limited** for the construction of natural gas pipeline system in Lower Austria by NIOGAS, Niederosterreich Gasvertriebs A.G., the Lower Austria organisation responsible for the distribution of gas fuel was officially announced. The gas will be used mainly for industrial purposes.

The pipeline system will cover a total of 160 miles and CJB will use the technical services of their American associates, Williams Bros. of Tulsa, Oklahoma. Austrian sub-contractors will carry out a considerable part of the work and Austrian labour and equipment will be used.

The British Transport Commission has placed a contract with **J. Stone & Co. (Deptford) Ltd.** for the supply of 30 Stone-Maybach Mekydro twin hydraulic transmissions for 2,000 h.p. Diesel hydraulic locomotives to be built at the Swindon Works of the Western Region.

J. Stone & Co. (Deptford) Ltd., have the exclusive manufacturing and selling rights in the United Kingdom for these hydraulic transmissions from Maybach Motorenbau G.m.B.H., Germany.

Heenan and Froude Ltd., Worcester, have received an order from Chantiers de l'Atlantique, Penhoet, France for a Froude Dynamometer type FA1030 with a capacity of 12,500 bhp at 350/600 rpm.

Following an order in 1955 for a large Froude Dynamometer of 10,000 bhp Wartsila-Koncernen A/B, Helsinki, Finland, have now ordered a Froude type FA4 Dynamometer of 1,500 bhp at 565/1000 rpm.

Classified Advertisements

The rate for all classified advertisements is 9d. per word : in bold print 1s. per word : minimum order 10s. Box-number advertisements 1s. extra. Instructions, together with remittance, must be received not later than the 1st of each month for advertisements to appear in the same month's issue.

WANTED

Copies of the February 1957 issue of THE ENGINEERS' DIGEST are urgently required. 4/6d. each will be paid for copies in good condition returned to The Subscription Department, THE ENGINEERS' DIGEST, 120 Wigmore Street, London, W.1.

BALL AND ROLLER BEARINGS, ETC. WANTED!! ALSO SURPLUS GOODS—ESPECIALLY HAND TOOLS—OF ALL DESCRIPTIONS. R. PORDES, 138, NEW CAVENDISH STREET, LONDON, W.1, MUeum 5250.

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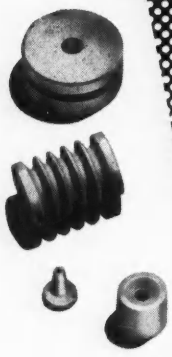
The many mechanical applications of SINTOX industrial ceramic will be of immense interest to the designer and mechanical engineer. The remarkable resistance to abrasion of SINTOX makes it particularly suitable for such uses as inserts and supports at points where rapid wear presents a problem. Already it has made a name for itself in the Textile industry, where the advent of artificial fibres brought entirely new problems. Thread guides made of SINTOX have been proved to have up to a hundred times the life of those made of hardened steel.



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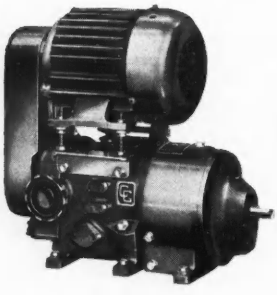

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BOOKS RECEIVED

Transmission Circuits. By Everard M. Williams, Ph.D., and James B. Woodford, Jr., D.Sc. 164 pp., 77 illustrations. Publishers : The Macmillan Company, N.Y., and 10 South Audley Street, London, W.1. Price : 30/-.

Covering the principles of electrical networks and conductor systems for energy and information transmission, this concise but instructive volume covers its subject in a straightforward manner. Although Professors Williams and Woodford have assembled the work primarily for teaching, rather than for reference, there is no doubt that this book is rich in content for students. Practical applications of the theory developed involve relatively little " technique ", especially that of the semi-empirical character involved in many fields. As a result, students can rapidly reach the stage of responsible self-directed activity in solving many practical problems of a technical or economic nature. Moreover, although a relatively simple fundamental theory has been utilized, the solutions of some problems frequently necessitate considerable analytical ingenuity on the part of the student.

A selection of typical problems is included for solution by students, these being of three distinct types, i.e., (1) a few examples requiring little more than substitution in expressions ; (2) problems requiring development or proof of aspects of the fundamental theory, deliberately omitted in the text ; and (3) problems of a professional nature, intended to challenge the capacity of students as engineers. Many of these latter problems are derived from recent developments in the field and are of current interest.

Basic Physics. By Alexander Efron, E.E., Ph.D. 724 pp., 800 illustrations. Publishers : John F. Rider Publisher, Inc., 116 West 14th Street, New York 11, U.S.A. Price : $7.60.

Comprising two volumes, combined in one binding, *Basic Physics* is undoubtedly one of the best, most readable, and thoroughly up-to-date books of its kind ever produced. The author has adopted a psychologically organized " spiral " approach to the subject, in which an overall picture is first presented, followed by a more penetrating and analytical study at intermediate level. Thus, Volume I is essentially descriptive in its make-up, while Volume II is more searching and mathematical.

Profuse illustrations, coupled with descriptions of basic demonstration experiments and the use of model problems of graduated difficulty, serve to generate and maintain student interest, making this thoroughly effective and useful textbook even more outstanding and instructive.

Stereophonic Sound. By Norman H. Crowhurst. 128 pp., 61 illustrations. Publishers : John F. Rider Publisher, Inc., 116 West 14th Street, New York, N.Y., U.S.A. Price : $2.25.

Providing all the information required on the subject of stereophonic sound recording and reproduction, this interesting book is the first true assessment of what is essentially a new and exciting medium. The author has much to say, and says it simply and well, whether it be an elementary exposition of the theory of stereophonic sound or a discussion of the various systems available or likely to become available.

In addition to details of basic binaural listening systems, in which realistic " three-dimensional " sound reproduction is achieved by the use of separate microphones and earphones for each ear, the author, an authority on his subject, covers stereosonic, coded-stereosonic, and two- and three-channel stereophonic systems, and their use with radio, disc, tape, and other media in the home, the concert-hall, the theatre, and the cinema. Full details of various makes of stereophonic equipment are included, together with practical information on the selection and location of loudspeakers for optimum reproduction.

An Outline of Great Western Locomotive Practice. By H. Holcroft. 176 pp., 150 illustrations. Publishers : Ian Allan Ltd., and the Locomotive Publishing Co., Craven House, Hampton Court, Surrey. Price : 25/-.

The Great Western Railway was the only English railway to preserve its identity from the time of incorporation to the day of unification by British Railways. During a period of 110 years (1837–1947), much has been written about the locomotives of the Great Western, their design, construction, operation, maintenance, and performance, but these contributions are at best fragmentary. Consequently, the object of this work is to present an overall picture of the progress achieved over the years. The result is an eminently successful and absorbing account of the G.W.R. from the days when the line from London to Bristol was built to Brunel's 7-ft gauge, and of some of the great engineers who were instrumental in perfecting its locomotives, ranging from Daniel Gooch and Joseph and George Armstrong to William Dean, Churchward, and Hawksworth.

Garcke's Manual of Electricity Supp'y, 1956–1957. Compiled under the supervision of Frederick C. Garrett. 836 pp. Publishers : Electrical Press Limited, 19/20 Noel Street, London, W.1. Price : 77/6.

This new edition (Volume 54) of Garcke's Manual is, as always, an invaluable aid to all those interested in a statistical record of the British Electricity and allied manufacturing industries.

The book is conveniently divided into sections, including the Central Electricity Authority, Area Boards in England and Wales, Electricity Authorities in Scotland, Ireland, etc., Electrical Plant and Allied Manufacturing Companies, and a Directory of Executive Personnel. In addition, a general survey is included, comprising a statistical review of the progress of electricity supply, based on the annual reports of the Electricity Authorities in England, Wales, and Scotland, and a summary of nuclear power development.

LATEST INDUSTRIAL LITERATURE

1. Box-Type Electric Furnaces. A selection from a wide range of electrically heated box-type furnaces is given in a well-produced 12-page illustrated booklet. The box-type furnaces described may be used for most industrial heating operations, and temperature limitations are the same as for any other electric resistance furnace, the maximum range being in the region of 1200°C.

Details are also included of furnace loading, air circulation, precipitation hardening, solution heat treatment, etc.

2. Protective Coatings. Details are given in a 12-page illustrated booklet of protective coatings formulated primarily as lining materials for mobile, marine, and static tanks carrying a wide variety of aggressive chemicals, petroleum products, crude oils, vegetable oils, edible oils, etc., all of which tend to rapid corrosion of unprotected metal surfaces with subsequent contamination of the contents of the vessel. These coatings are also suitable for plant equipment in chemical and food trades and in oil refineries.

3. Air Filters. Information on a new air filter is contained in an illustrated 8-page leaflet, the air filtration unit described combining a dry-plate electrostatic precipitator and an automatic renewing media filter. Dust particles are electrostatically attracted to the dry plates of the precipitator section, adhering to each other on the plates. When the build-up becomes great enough, the accumulation is carried by the air stream onto the automatically renewing media of the storage section, where the dirt and used media are tightly wound into a compact roll for easy disposal.

4. Gravity Roller Conveyors. Specifications and details of gravity roller conveyors are incorporated in an illustrated 20-page brochure. In these units, reversed angle frames protect not only the operator's hands and clothes by shielding spindle-ends, but also prevent the accumulation of dust and dirt. A further advantage of reversed angle frames is the ease with which side guards, side tables, etc., can be fitted.

Each spindle acts as a tie-bar, thus ensuring maximum rigidity. There are no wires, cross braces, or underside obstructions, and rollers are easily withdrawn by the removal of a lock-nut and thrust collar. In addition, side members are multi-punched at 1-in. intervals, thereby enabling the user to alter the pitch of the rollers to accommodate a change in load.

Examples are shown of light-, medium-, and heavy-duty types of roller conveyors, together with a section on ancillary equipment, adjustable and fixed stands, etc.

5. Digital Counting Equipment. Details are provided in a neatly produced 12-page brochure of a range of digital counting equipment, including frequency meters and universal counter-timers, microsecond chronometers, and digital pulse delay generators. In addition, details are given of transducers for shaft speed control and techometry and of a stabilized power unit specially developed to fill the need for an efficient and cheap unit which can be built into experimental or production equipment.

A supplementary 16-page brochure covers a range of telecommunications equipment, including a new high-stability H.F. communications receiver, teletype receivers, wide-band transformers, 12-way coaxial switches, and directional aerial arrays.

6. Screw-Thread Inserts. A well-produced folder contains a number of pamphlets, bulletins, and descriptive literature dealing with a range of screw-thread inserts which are essentially precision-formed thread liners made from high-tensile, stainless-steel wire held to fine limits and special surface finish. They will not rust or corrode, and bolts or studs fitted into them will not seize under high temperature conditions. They are available in a wide range of sizes, and each insert is supplied in five standard lengths, though, for special applications, non-standard lengths or sizes can be made.

These screw threads have a slightly larger free diameter than the hole into which they are installed, and are compressed before installation in an inserting tool for quick seating in the tapped hole. Consequently, they are self-locking, and no amount of vibration or screw turning will loosen them. However, they can be quickly and easily removed with an extracting tool, if necessary. When assembled in tapped holes, the inserts conform to the relevant British Standard Specification for screw threads.

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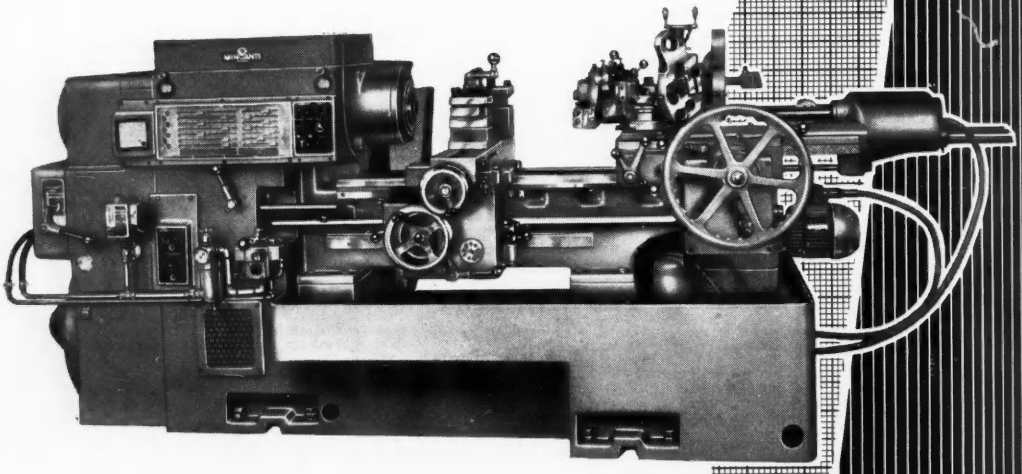

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Newton Chambers

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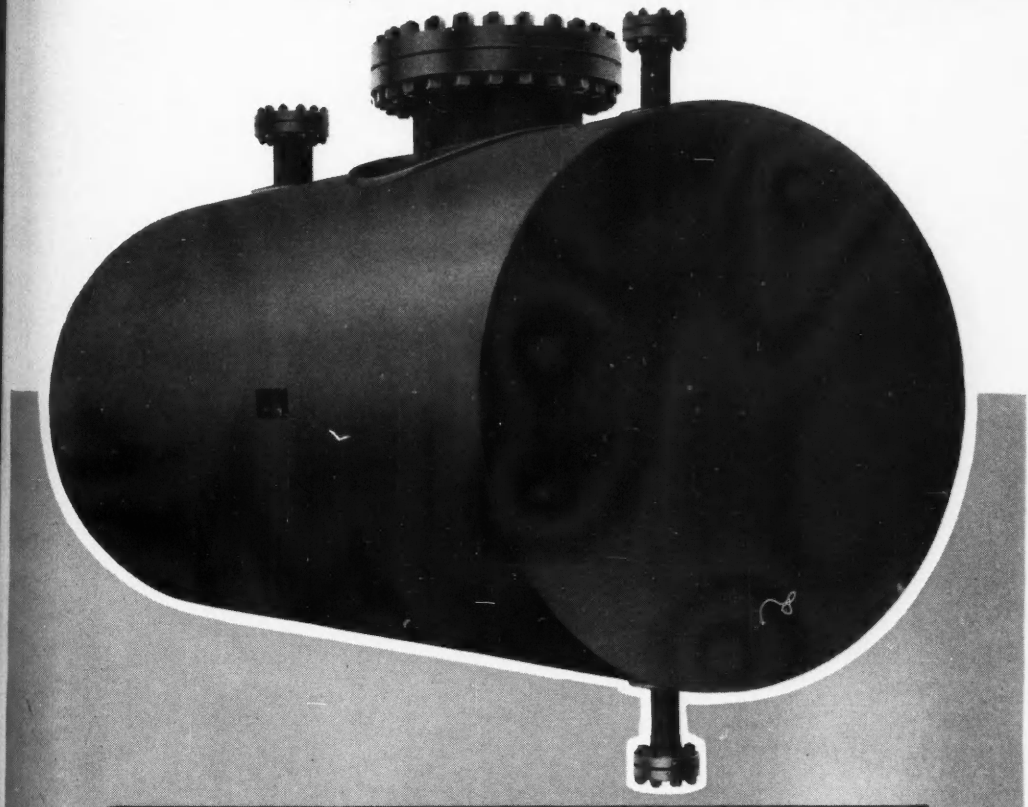
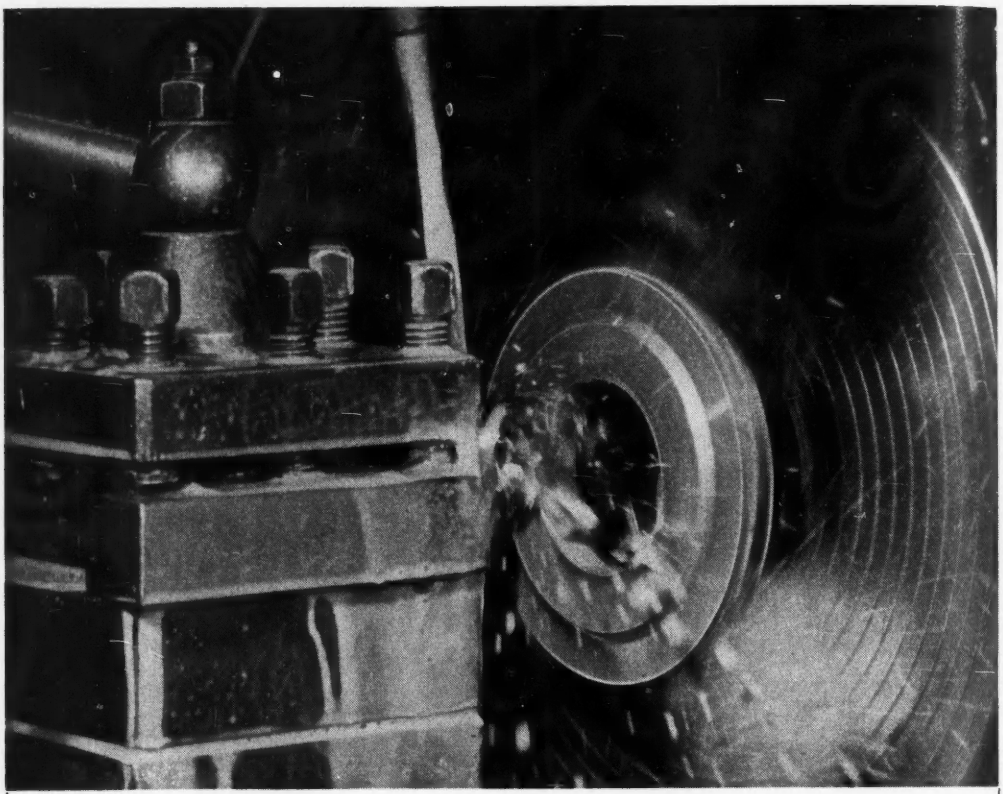


Newton Chambers have pleasure in announcing that they are now recognised by Lloyds Register of Shipping for the manufacture of Lloyds Class 1. Fusion Welded Pressure Vessels.

▶ *Please forward your enquiries.*

NEWTON CHAMBERS & CO. LTD.
THORNCLIFFE, Nr. SHEFFIELD



There is danger here—danger to sight and limbs. But safety can so simply take the place of that danger. "Armourplate" glass shields give certain protection. And because the operator can see what is happening he works more confidently and efficiently. Accident rates drop, and production rises when "Armourplate" glass shields are fitted.

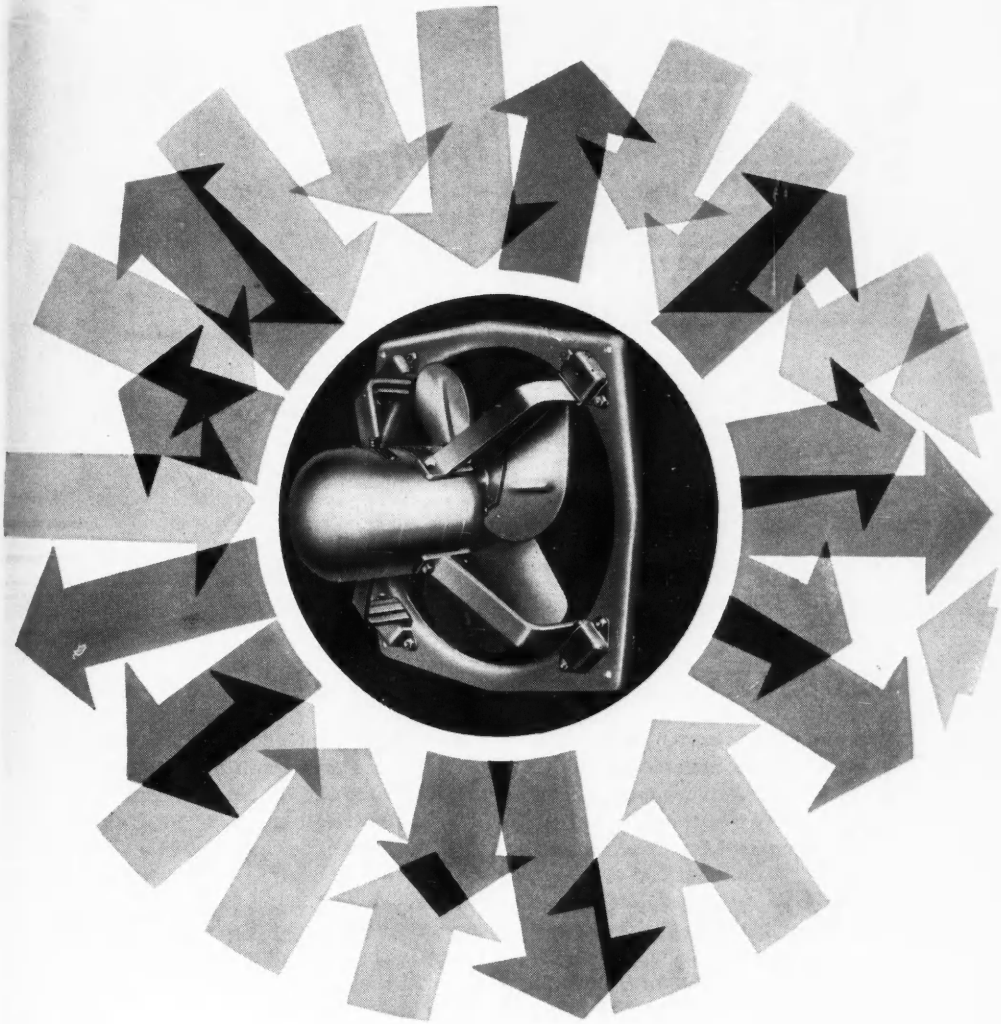
FOR SAFETY WITH VISION FIT

"ARMOURPLATE" GLASS

PILKINGTON BROTHERS LIMITED

Consult the Technical Sales and Service Department at St. Helens, Lancs. Telephone: St. Helens 4001
or Selwyn House, Cleveland Row, St. James's, London, S.W.1. Telephone: Whitehall 5672-6

"ARMOURPLATE" is a registered trade mark of Pilkington Brothers Limited. Supplies are available through the usual trade channels



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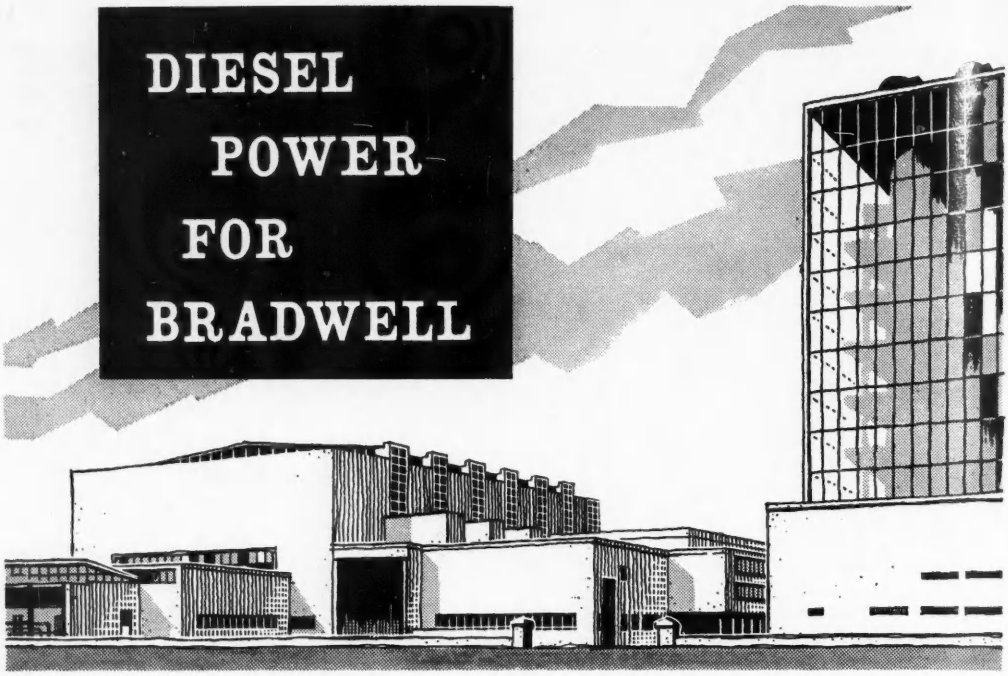
fresh air all the time with

G.E.C. PROPELLER FANS

Send for publication V 1220 giving full details of all G.E.C. propeller fans.

The General Electric Company Limited, Magnet House, Kingsway, London, W.C.2.

DIESEL POWER FOR BRADWELL



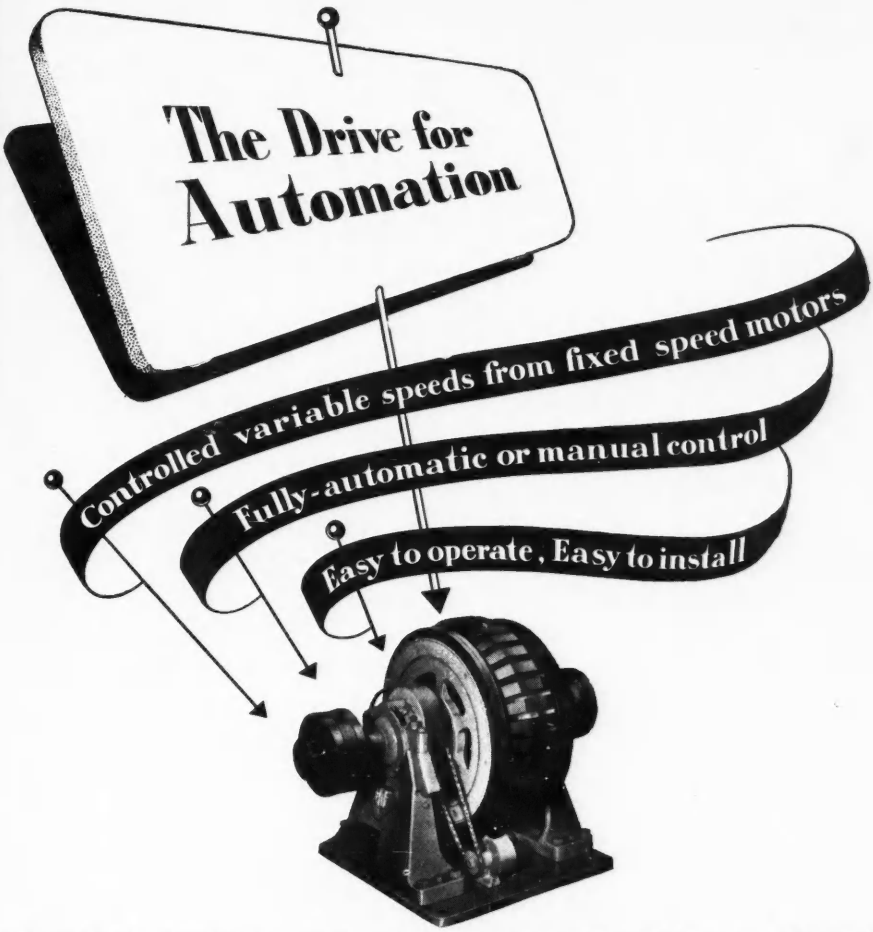
CROSSLEY engines for essential duties

Crossley Diesels have been chosen for yet another new nuclear power station, at present being constructed by the Nuclear Power Plant Company. Engines of the same design are in service or being installed in the United Kingdom Atomic Energy Authority's power stations at Calder Hall "A" and "B", Chapel Cross and Dounreay. Permanently installed will be three Crossley "ES Vee" 10 cylinder two-cycle Scavenge Pump Diesel engines, each rated at 620 b.h.p. at 1000 revolutions per minute and driving 450 kW. Lancashire Dynamo and Crypto alternators. These are automatic standby sets for the provision of current for essential services in the event of mains failure. The sets are supplied for Bradwell to Messrs. A. Reyrolle and Co. Ltd. Already installed on site is an "HSN 6" six cylinder two-cycle engine driving a 412 kW. alternator, this unit providing power on site during the construction period. Later two Goliath cranes will be installed, each powered by an "HSN 3" three cylinder straight line two-cycle Scavenge Pump Diesel engine driving Clarke Chapman 250 kW. alternators, one unit being mounted in one of the legs of each crane. These two sets are being supplied to the order of Messrs. Clarke Chapman & Co. Ltd.

CROSSLEY DIESEL ENGINES

CROSSLEY BROTHERS LIMITED · OPENSHAW · MANCHESTER 11

ΦC423


The Drive for Automation
Controlled variable speeds from fixed speed motors
Fully-automatic or manual control
Easy to operate, Easy to install

HEENAN-DYNAMATIC

VARIABLE SPEED COUPLINGS

Innumerable examples, in the widest variety of applications, prove their versatility in solving almost any problem of controlled speeds, and response to almost any kind of signal.

★ **In this era of rising costs we are pleased to announce**

SUBSTANTIAL PRICE REDUCTIONS

on stock sizes, made possible through increasing turnover and improved methods of production.

HEENAN & FROUDE LIMITED
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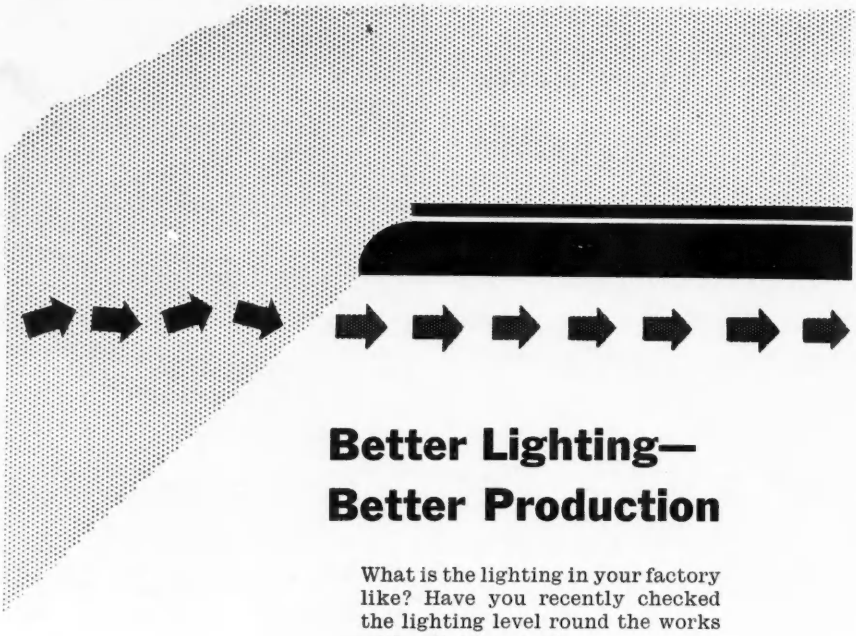


Better Lighting—Better Production

What is the lighting in your factory like? Have you recently checked the lighting level round the works with a light meter?

The *right* lighting has a significant effect on the speed and accuracy of production. When its strength, position and type is suitable for each job the craftsman can give full play to his skill, and the works engineer can do full justice to his shop.

Good lighting is only one of the many ways in which electricity is playing a vital part in the drive for higher productivity.

Electricity for Productivity

Ask your ELECTRICITY BOARD for advice and information, or get in touch with E.D.A. They can lend you, without charge, films about the uses of electricity in industry. E.D.A. are also publishing a series of books on Electricity and Productivity. Titles now available are: Lighting in Industry, Electric Resistance Heating, Electric Motors and Controls, Higher Production, Materials Handling, and the latest addition to the series, Induction and Dielectric Heating. Price 8/6, or 9/- post free.

Issued by the British Electrical Development Association, 2 Savoy Hill, London, W.C.2

Switch from this—

to this

and step up production . . .

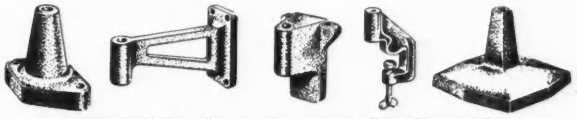
For working within close limits, an Anglepoise is simply indispensable. However good a worker and his eyes may be, he must see the job. This applies in all fine work, drilling, assembling, etc., where instantly adjustable close-to-the-job lighting is a sheer necessity.

ANGLEPOISE throws a clear, concentrated light right on and into the work, not in the operator's eyes, follows the job from any position or angle, degree by degree, at a finger-touch, and 'stays put' in any required position—and out of the way when not needed. It needs only a low-powered bulb for high-class results—a big saving on the lighting bill (it can be supplied with a small shade for low voltage systems). Why not learn more about this fine lamp by sending for Booklet E.D.?

TERRY Anglepoise LAMP
Reqd.

Sole Makers: HERBERT TERRY & SONS LTD · REDDITCH · WORCESTERSHIRE

***A SUGGESTION FOR MACHINE MANUFACTURERS:—**
Why not fit your products with Anglepoise? We will submit samples on approval.



Some of the alternative bases for all models HT208

ARCHDALE

HEAVY DUTY VERTICALS

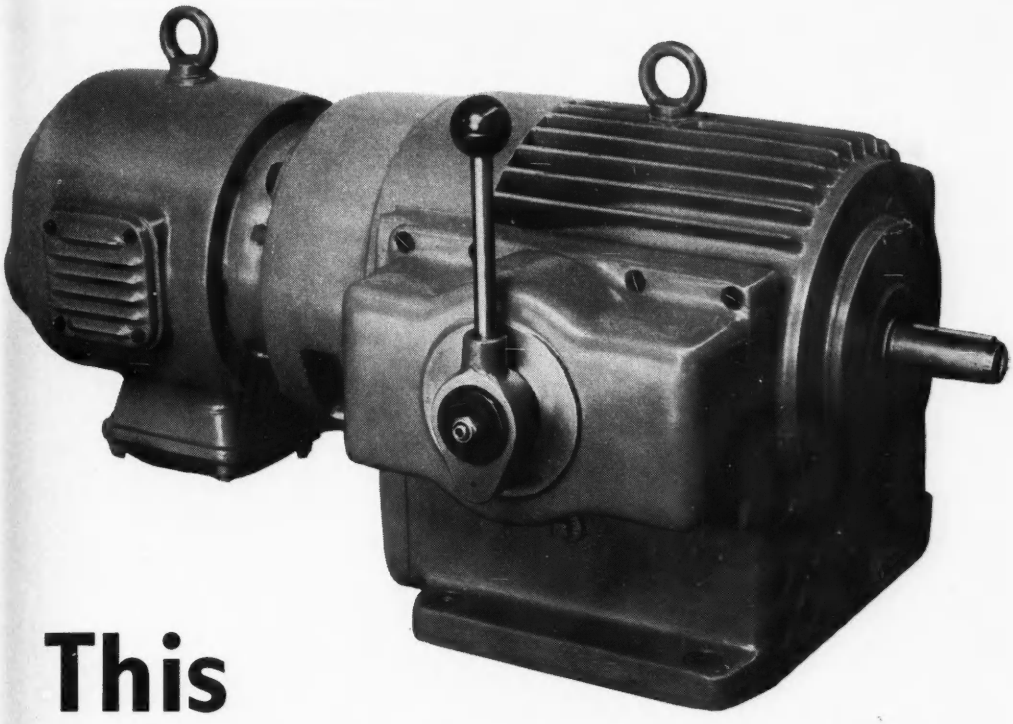
for drilling up to 4" in steel!

THIS photograph, taken at the Lincoln Works of Ruston Bucyrus Ltd., shows their wise choice in selecting ARCHDALE for heavy duty vertical drilling machines. Built with a strength and rigidity to match the power required for continuous heavy work, these machines will drill up to 4 in. dia., in M.S., the 30 in. machine, 3 in. dia., and the 28 in. machine 1⅜ in. dia. All three can be supplied with plain, elevating or compound tables.

JAMES ARCHDALE & CO LTD · LEDSAM STREET · BIRMINGHAM 16

SOLE AGENT: ALFRED HERBERT LTD, COVENTRY

A member of the Staveley Coal & Iron Co, Ltd. Group.



This

HYDRAULIC TRANSMISSION UNIT

The Churchill-Sturm Hydraulic Drive

is ideal for nearly all types of machinery, such as Wood-Working, Textile, Glass-making, Welding, Paper-Making & Printing Machines; Machine Tools, Testing Equipment, Mechanical Handling Plant, Winches & Hoists, Kilns & Furnaces, Chemical Plant, Wire & Tube Draw Benches, etc. etc.

Illustrated is Model C24 (3½ H.P.) Hydraulic Drive with flange-mounted motor.

Made in NINE SIZES from 1¼ to 32 H.P.

. . . . driven by a constant speed motor, combines the functions of gearbox, clutch and brake. The speed of the output shaft is infinitely variable over a wide range in either direction of rotation; up to about one fifth of the maximum speed the torque developed is constant and over the remainder of the speed range the power output is constant. All moving parts are automatically lubricated and protected against overload; the unit has a high efficiency under all conditions and it requires virtually no maintenance.

CHURCHILL-STURM LIMITED

COVENTRY RD SOUTH YARDLEY BIRMINGHAM 25

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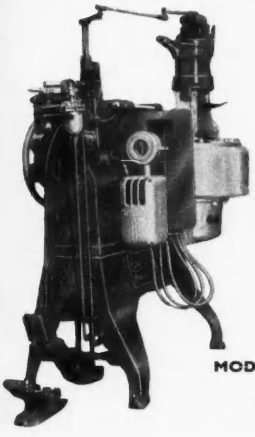
NEVEN

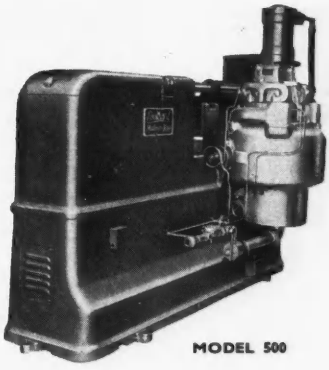
There are no better diamond tools than those manufactured by Impregnated Diamond Products Limited of Gloucester.

British Built

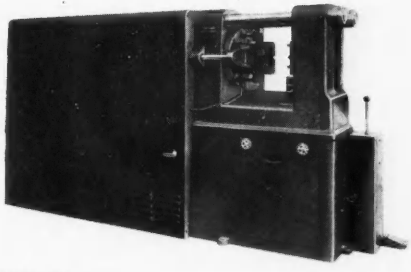
COULTHARD MADISON-KIPP



MODEL 215E



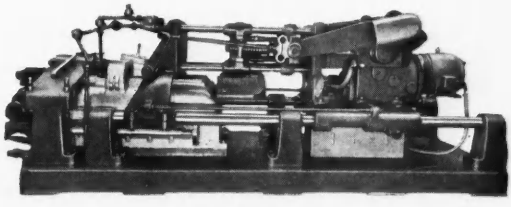
MODEL 500



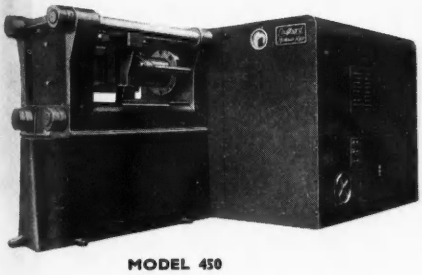
MODEL 400

Complete

DIECASTING SERVICE



MODEL 4

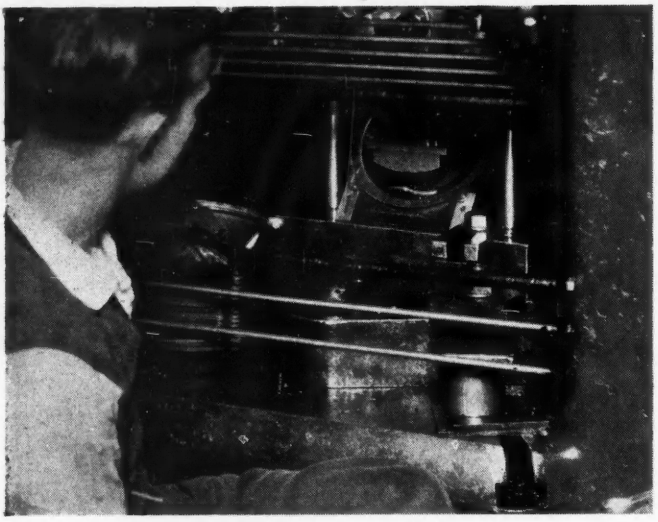


MODEL 450

Efficient

WM. COULTHARD & COMPANY LTD.
DURRANHILL ENGINEERING WORKS
CARLISLE

TEL. 2148 TEL. 2148



Steels for Press Tools

" 476 ". For tools operating under severe conditions of wear and abrasion or when maximum runs are desired. Air hardening, machinable. Applications include dies and punches for blanking steel sheet and plate, high silicon transformer materials, stainless steel and iron, brass, copper, zinc. Also for deep drawing dies, cupping dies, forming dies.

" L.T.A.H." Deep hardening in air at 840 deg./860 deg. C. with minimum distortion. Tough and abrasion resistant. Low decarburization. Machinable. Specially for tools of heavy or intricate section, heavy forming dies, blanking dies, trimming dies, notching dies, heavy duty punches, spindles, stripper plates, bending tools.

" S.C.V." A hard tough steel which resists sinking. For cutting dies, drawing and rivet dies, stamping and blanking dies, pressing dies, coining dies.

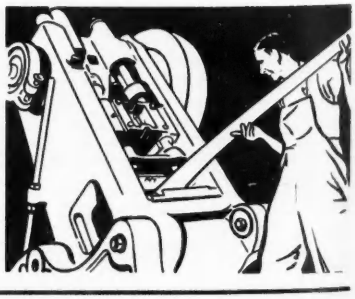
" NEWHALL ". An oil hardening non-deforming steel. Has a wide range of applications in press tool work when it is not desired to use more highly alloyed steels.

" PAX No. 2 ". Shock resisting steel with high impact strength and good wear-resistance. For punches and dies used on thick gauge materials and subject to heavy shock.

'SABEN' HIGH SPEED STEELS, HOT WORK STEELS

SANDERSON

A SABEN PRODUCT



SANDERSON BROTHERS AND NEWBOULD LIMITED, ATTERCLIFFE STEELWORKS, P.O. BOX 6, NEWHALL ROAD, SHEFFIELD 9

Humber's greatest Hawk

Fine bodywork welded by Saturn-Hivolt

Surge Injector Welding Units

Notable always for the highest standard of bodywork. Humber recently announced their greatest 'Hawk'. In this, as in many previous models, Saturn-Hivolt Surge Injector Welding equipment and Saturn Argon are used for many of the important welding operations. Saturn cutting and welding equipment has, for many years, played a big part in industry. The new Saturn-Hivolt Argon Arc Welding Machines offer the finest welding of aluminium and its alloys and stainless steel. Let us show you the complete range supplied and maintained from our many branches throughout the country.

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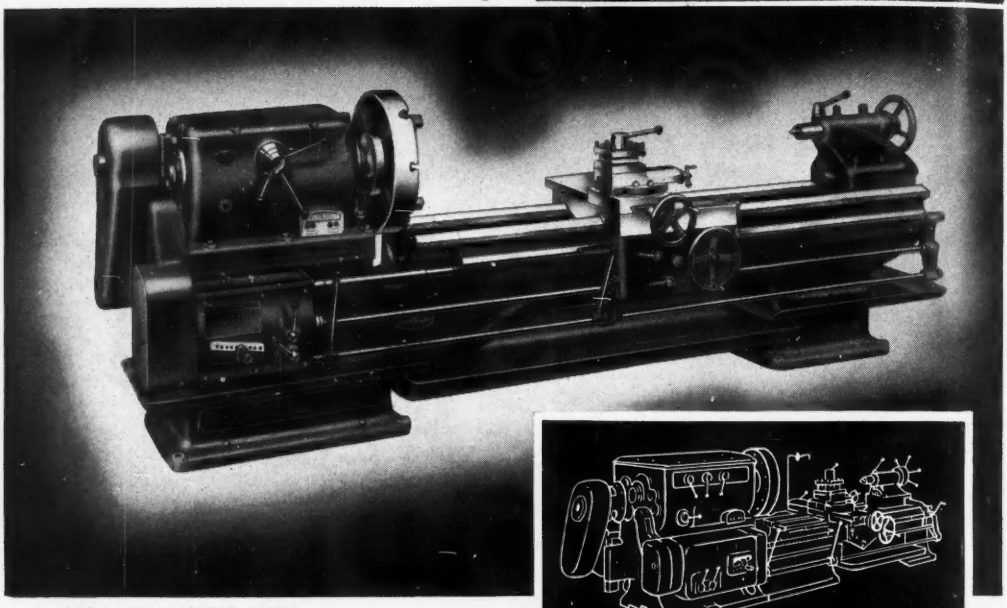
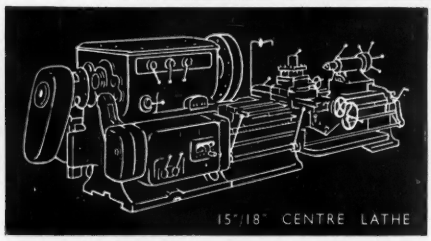
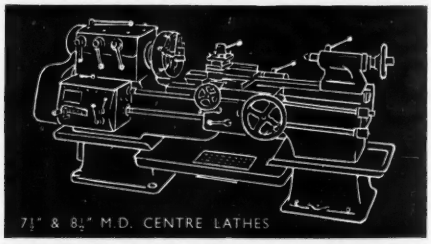
SUPERB LATHES by CROWTHORN



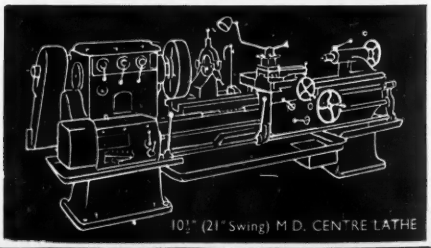
12"/12¼" H.D. CENTRE LATHE



15"/18" CENTRE LATHE



7½" & 8½" M.D. CENTRE LATHES



10½" (21" Swing) M.D. CENTRE LATHE

The well known versatility of Crowthorn lathes is further enhanced by the range of attachments. Almost any machining operation can be performed with consistent precision.

Please write for fully detailed literature.

CROWTHORN

CROWTHORN ENGINEERING COMPANY LIMITED

High Class—Machine Tool Makers

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Phone: STOCKPORT 7271-2-3 *Grams: CROWTOOL, REDDISH*

CL88

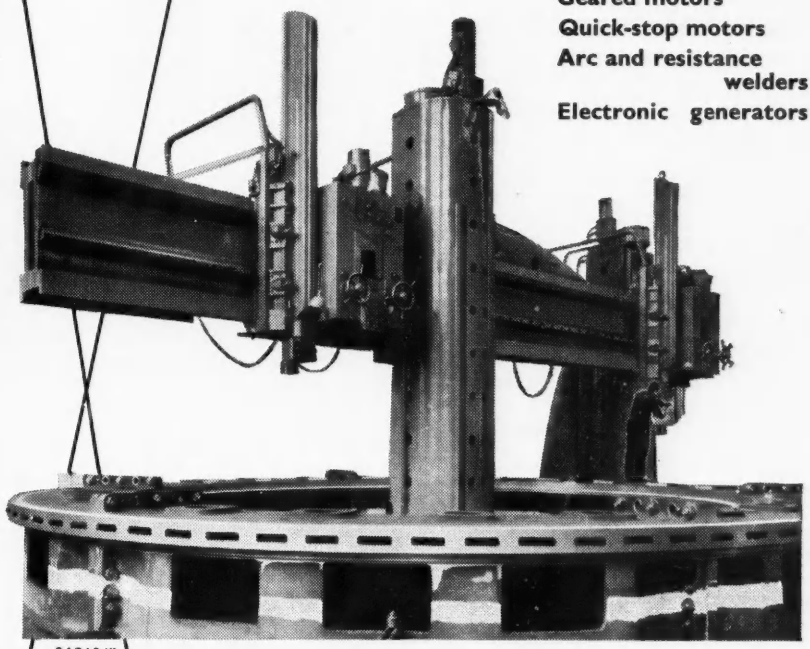
BROWN BOVERI

Electrical equipment
for machine tools

with from the simplest to full-automatic electrical control enables products to be held to closer tolerances, as well as boosting production and increasing reliability.

Our specialists will be only too pleased to advise you and help you solve your driving problems.

We supply in addition:
Electronic drives
Geared motors
Quick-stop motors
Arc and resistance welders
Electronic generators



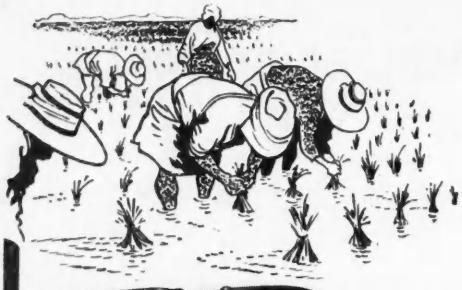
84362.XI

This Escher Wyss, Zürich, universal, vertical turning mill for workpieces up to 16 metres in diameter is equipped with Brown Boveri variable-speed drives, several synchronous ties and a large number of auxiliary motors. Maximum demands are imposed on the reliability of such drives and their control gear.

Our lengthy experience is also at your disposal.

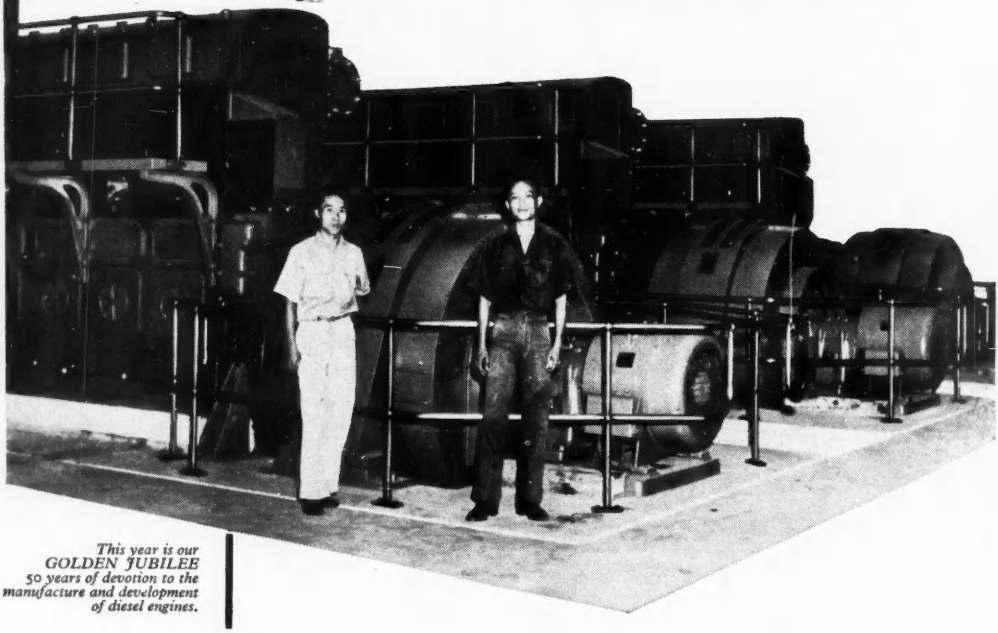
BROWN, BOVERI & CO., LTD., BADEN
SWITZERLAND

Representatives in most countries



Mirrlees

diesel power for THAILAND



This year is our GOLDEN JUBILEE 50 years of devotion to the manufacture and development of diesel engines.

Twenty years ago the need arose to build a port installation on Thailand's main river, the Menam Chao Phya, as close as possible to the capital Bangkok, to provide berthing, warehouses and wharfeside cranes. The initial stage was completed before the war and finality will soon be reached. The nature of the river prevented siting the port in the heart of the city; Bangkok's own electricity needs were rising rapidly; incoming equipment, interrupted by the war, placed higher demands on the port. For all these reasons it was decided that the port should have its own diesel power station. Five years ago, Mirrlees/Brush equipment won a contract for generating sets to meet the present demands and three Mirrlees K6 engines were supplied, running at 428 rpm, driving Brush 575 kW alternators.

These sets with their associated 3.5KV Brush switchgear transformers and auxiliaries are now operating in a very attractive 2 storey power station, having provision for 2 further sets, on what is virtually a swamp, on concrete foundations each supported by fifteen 36 cms. (14 in.) dia. piles 16 m. (52 feet 6 in.) long both vertical and raked.

Mirrlees diesels

MIRRLEES, BICKERTON AND DAY LIMITED

A Member of the BRUSH Group

HAZEL GROVE · STOCKPORT · CHESHIRE

Telephone: Stepping Hill 3841 (14 lines) Telegrams: 'Mirrlees Telex, Manchester'

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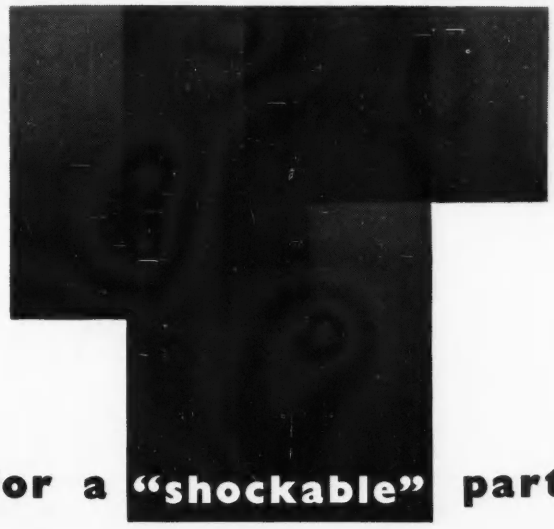
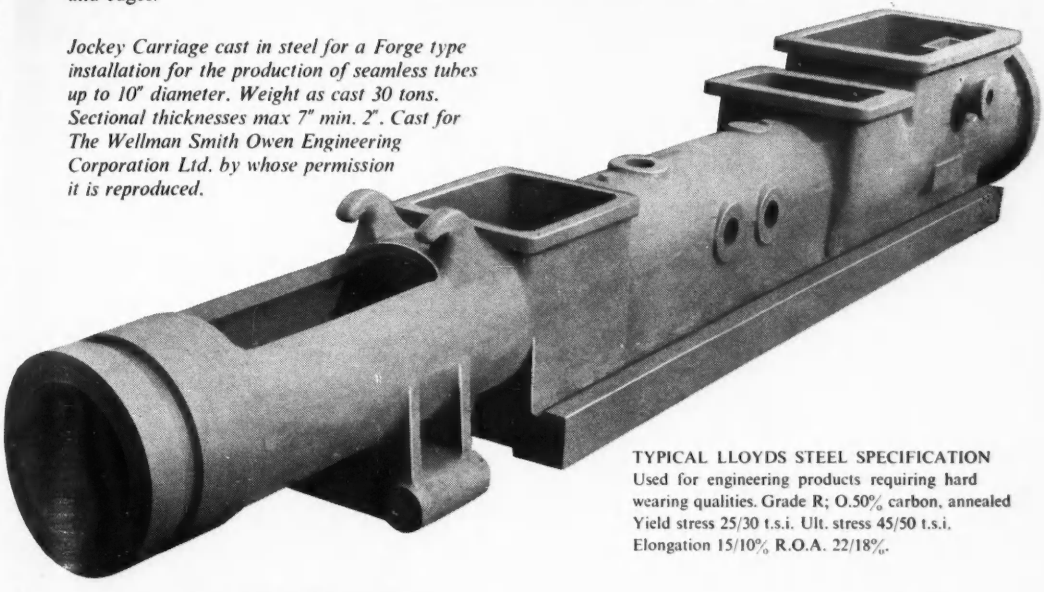


cast for a "shockable" part

This jockey carriage is cast in steel for a forge type of installation for the production of seamless tubes up to 10" diameter, and has to withstand unpredictable shock load. It is a good example of the versatility of steel casting, in that its sectional thickness varies from 2" to 7", essential requirements that make it almost impossible to fabricate by any other method.
Owing to good method planning this casting is free from defects and of especial interest is the fine finish. Note also the sectional thickness round the corners and edges.

Jockey Carriage cast in steel for a Forge type installation for the production of seamless tubes up to 10" diameter. Weight as cast 30 tons. Sectional thicknesses max 7" min. 2". Cast for The Wellman Smith Owen Engineering Corporation Ltd. by whose permission it is reproduced.



TYPICAL LLOYDS STEEL SPECIFICATION
Used for engineering products requiring hard wearing qualities. Grade R; O.50% carbon, annealed
Yield stress 25/30 t.s.i. Ult. stress 45/50 t.s.i.
Elongation 15/10% R.O.A. 22/18%.

LLOYDS ***Britain's best equipped steel Foundry***

F. H. LLOYD & CO. LTD., P.O. BOX No. 5, JAMES BRIDGE STEEL WORKS, WEDNESBURY, STAFFS. TELEPHONE JAMES BRIDGE 2401

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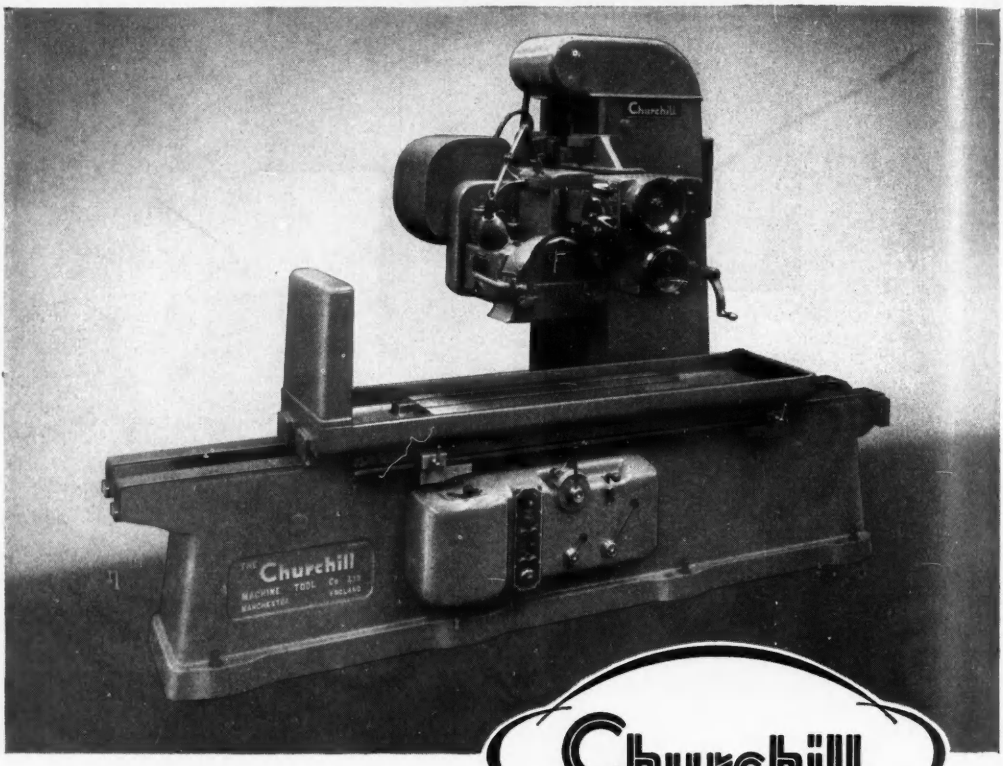

Churchill

'OSD'
OPEN-SIDE
SURFACE GRINDING MACHINE

This heavy duty Horizontal Spindle Surface Grinder fully meets modern requirements for a machine capable of highly accurate work at maximum production rates. Available in three sizes with work table capacities of 30in. by 15in., 48in. by 15in. and 72in. by 15in.

Designed for heavy duty and continuous high speed precision working.

Electronically controlled intermittent cross feed. Provision for accurate reversal when grinding recessed faces.

Variable automatic vertical feed with pre-set automatic cut-out.

Hydraulic table traverse up to 100 feet per minute.

Table traverse ways automatically lubricated from oil supply independent of hydraulic system.

Permanently protected precision ground slideways.

Electrically driven slow cross traverse for wheel truing.

Grinding wheel spindle electrically interlocked against starting until lubricating pump is running.

ASSOCIATED BRITISH MACHINE TOOL MAKERS LTD.

THE CHURCHILL MACHINE TOOL CO. LTD. BROADHEATH, NR. MANCHESTER

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PRECISION *plus* PRODUCTION

C663A

TAYLOR-HOBSON SURFACE FINISH

NOW INTRODUCE

model 100 *Portable* 'TALYSURF'

Designed for on-the-spot workshop applications, Model 100 'Talysurf' surface measuring instrument can easily be carried to a machine or bench as required. Small parts to be inspected are placed on the work-table, whilst four adjustable fences are provided to aid the location of cylindrical components.

TAYLOR, TAYLOR & HOBSON LTD. LEICESTER, England

The illustration shows the instrument in use checking the surface finish of a circular component after being ground on a Jones & Shipman universal grinding machine.

A Member of RANK PRECISION INDUSTRIES LTD

FOR HOISTING WITHOUT A HITCH!

If there is one factor more than another that would account for the ever-increasing demand for Morris electric hoist-blocks, it is the simplicity of their design and construction. As our sectional illustration shows, the motor, the straightforward reduction gear, the drum, powerful brake and robust contactor panel are supported by a welded steel frame. Thousands of users have already proved that this simple, practical arrangement results in dependable service even under adverse conditions—*in fact, hoisting without a hitch.*

Sizes ¼, ½, 1, 2, 3, 5, 7½ and 10-tons. Types for fixed, suspension, push travel, geared travel or for electric travel.

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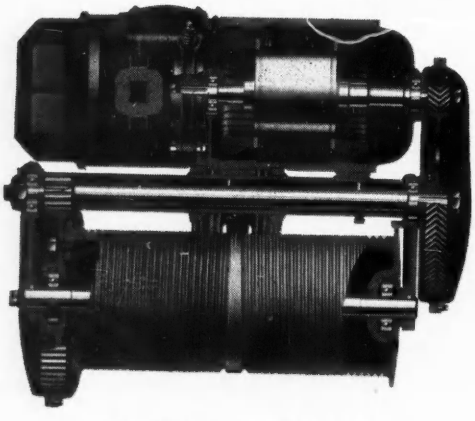

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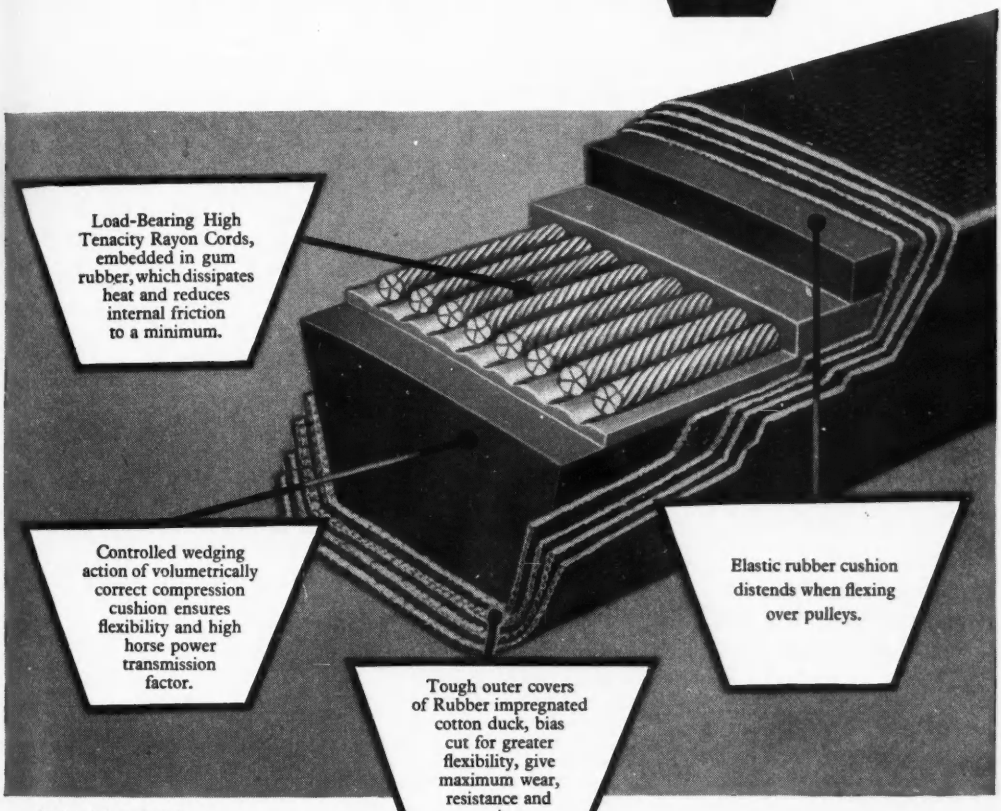
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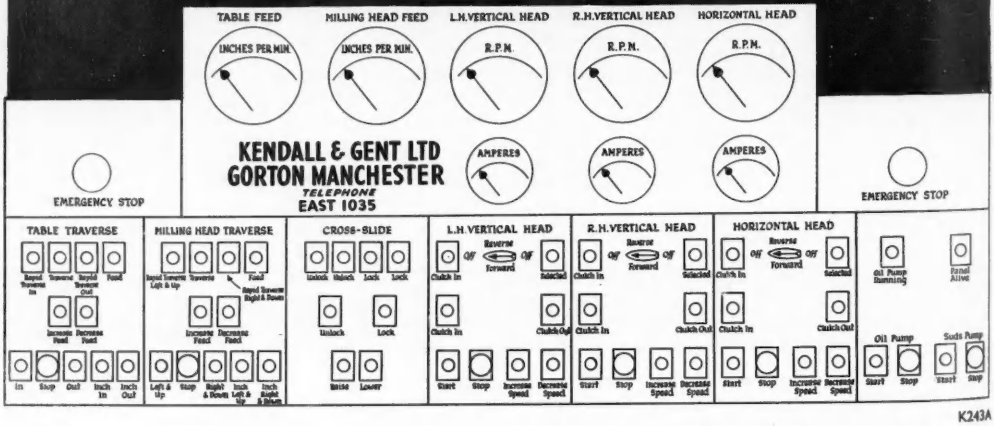

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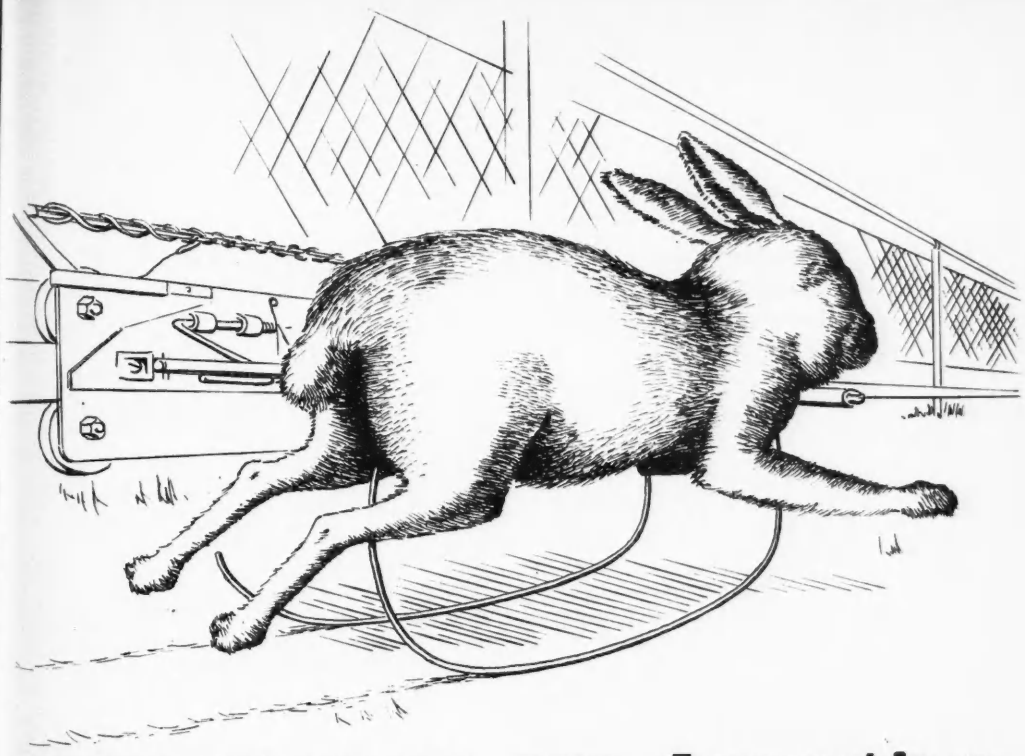

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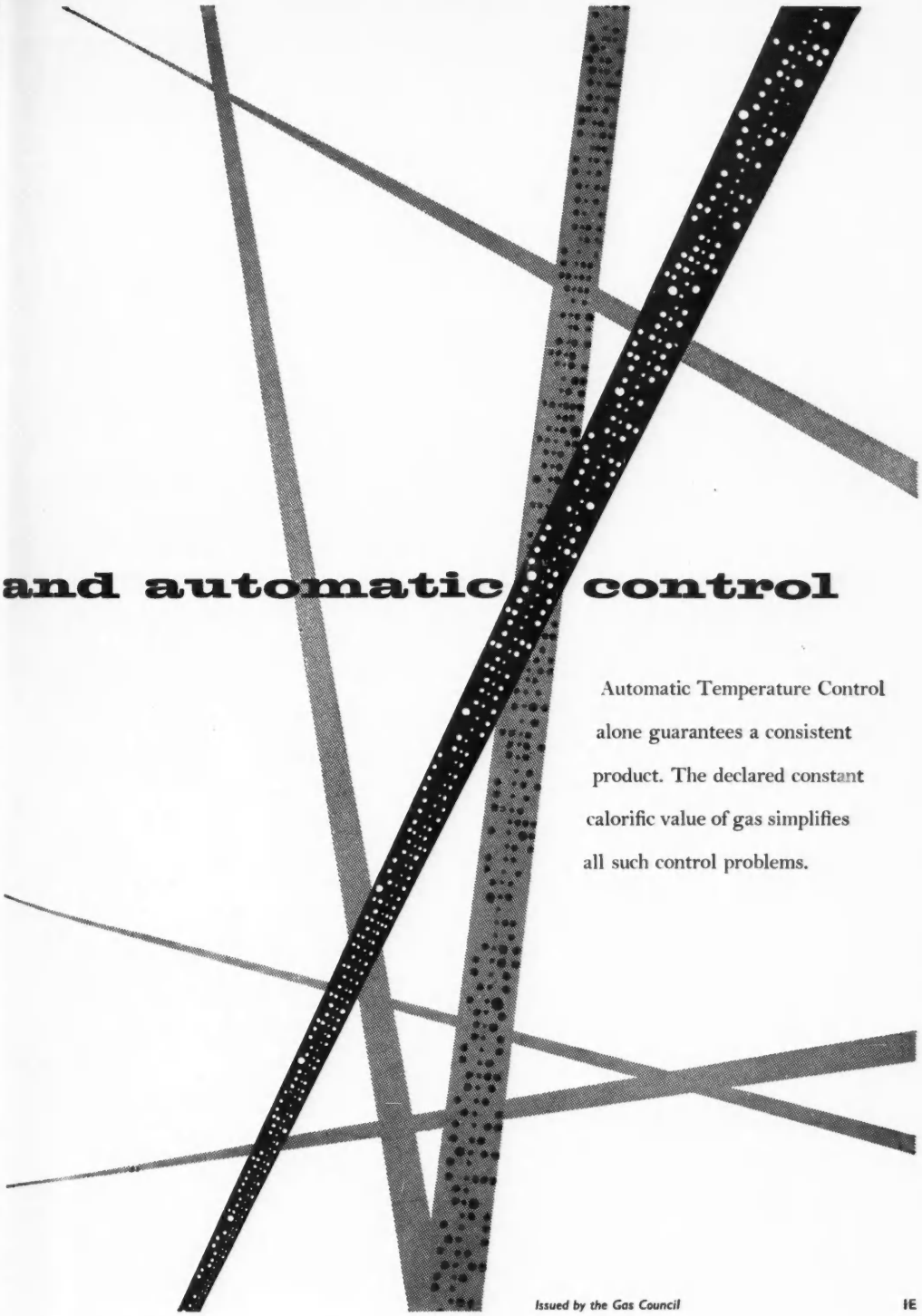

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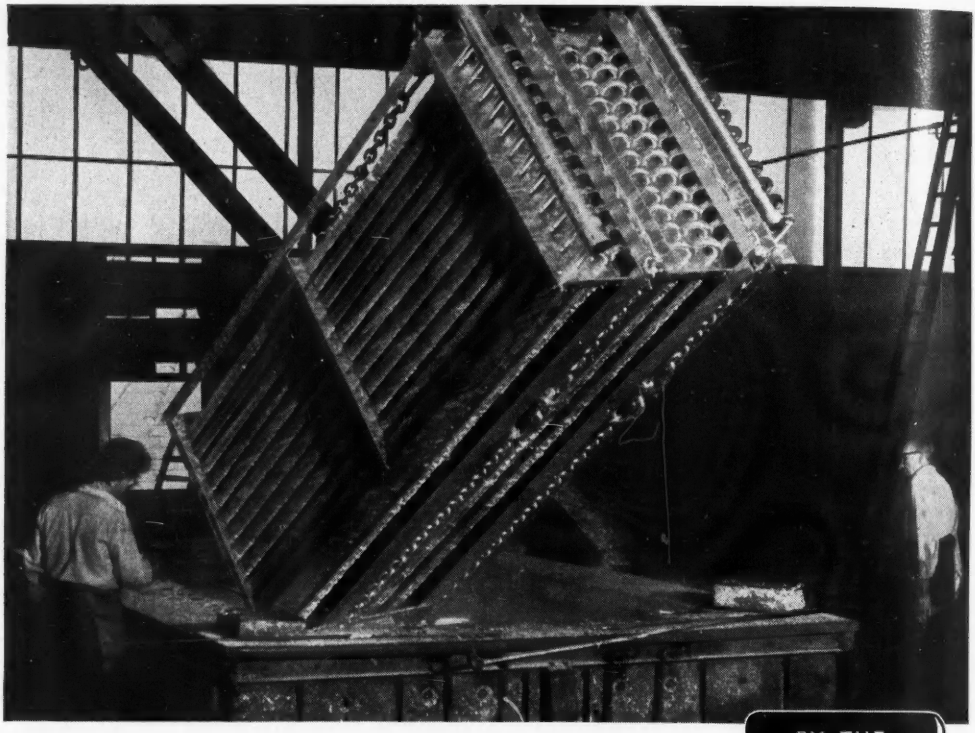

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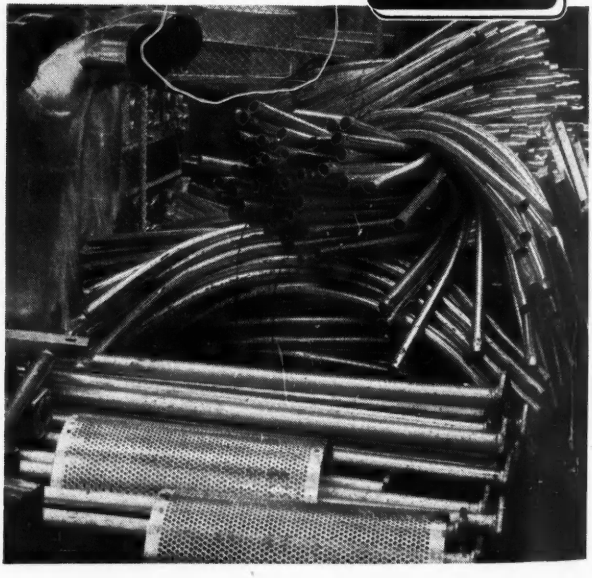

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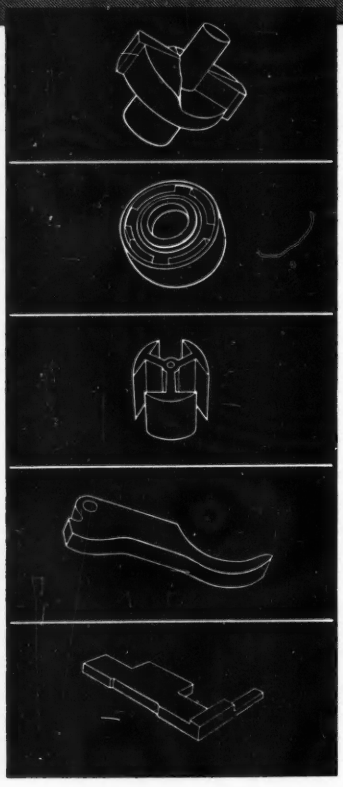

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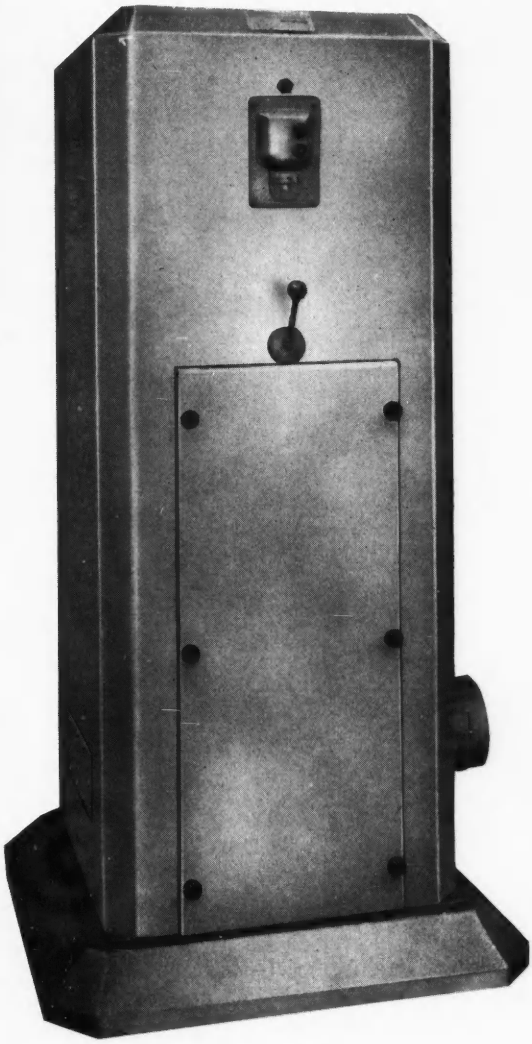

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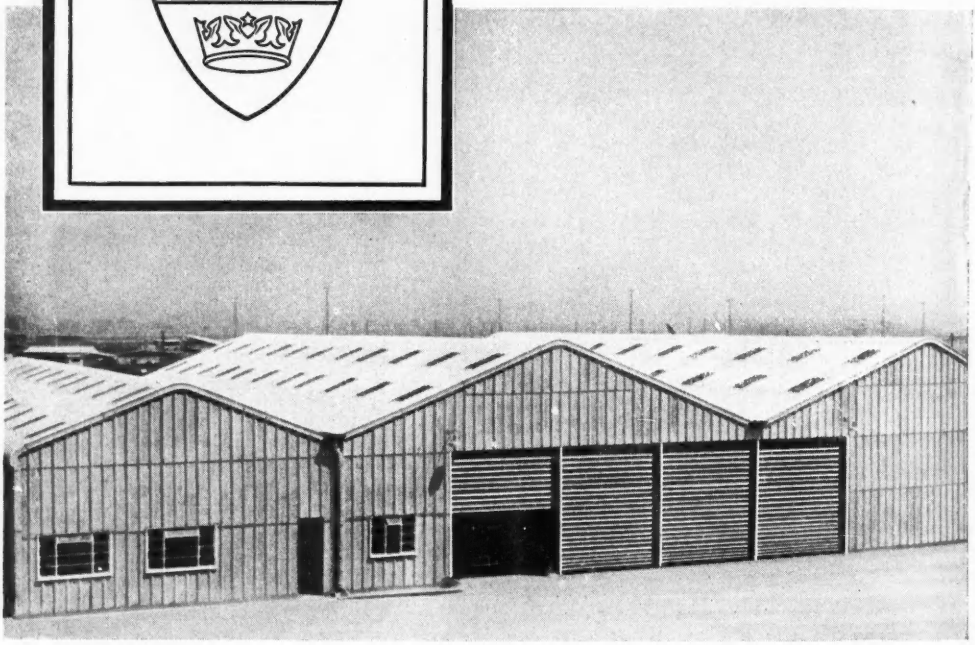

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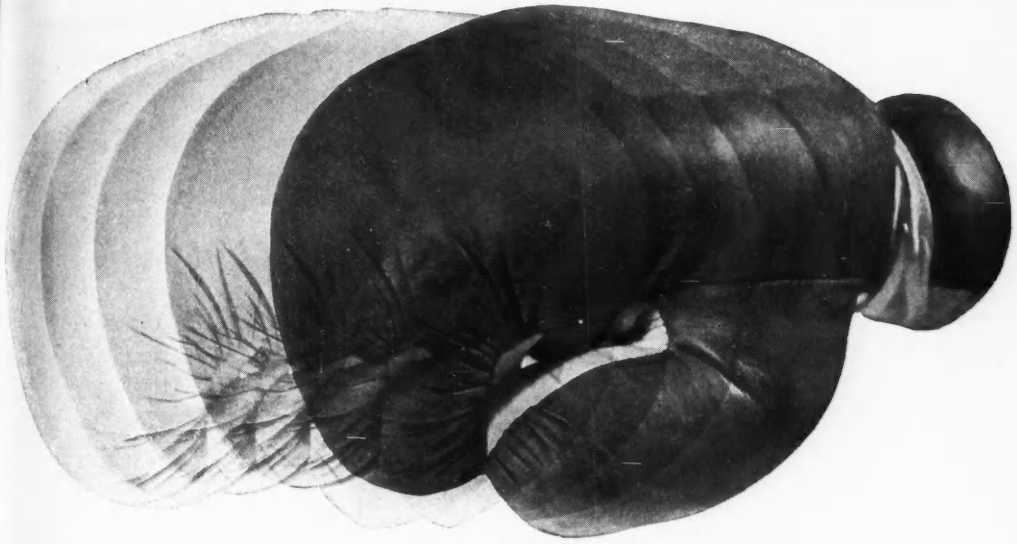

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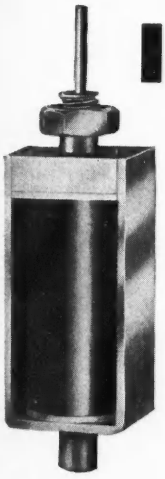

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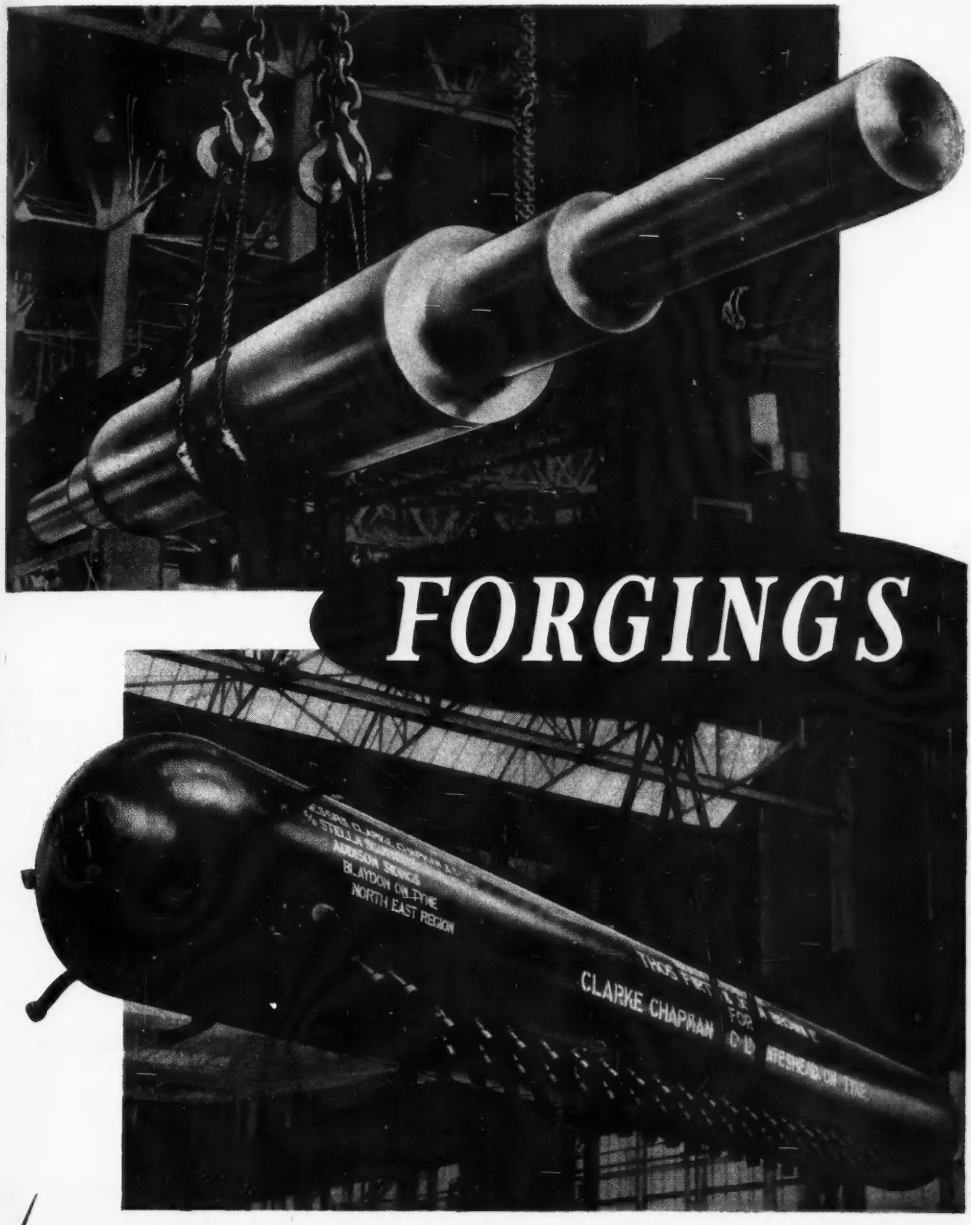

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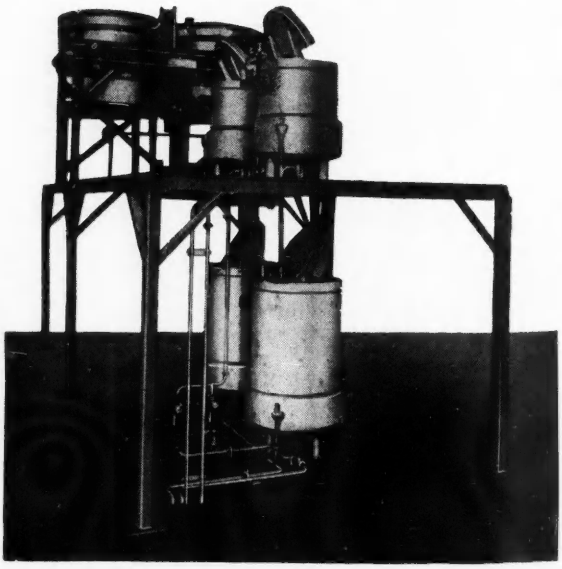

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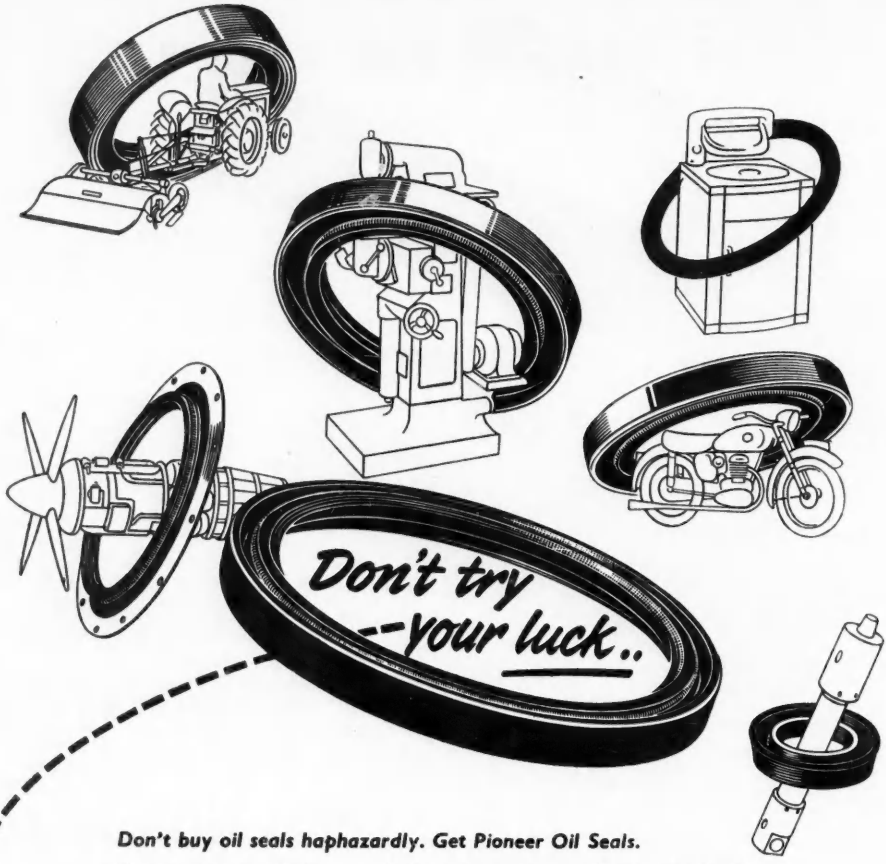

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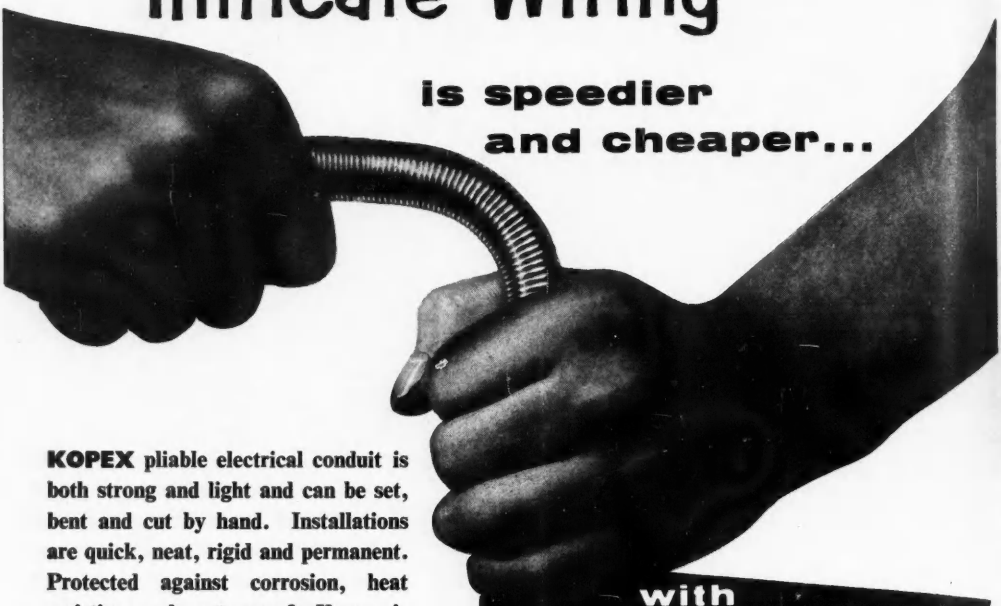

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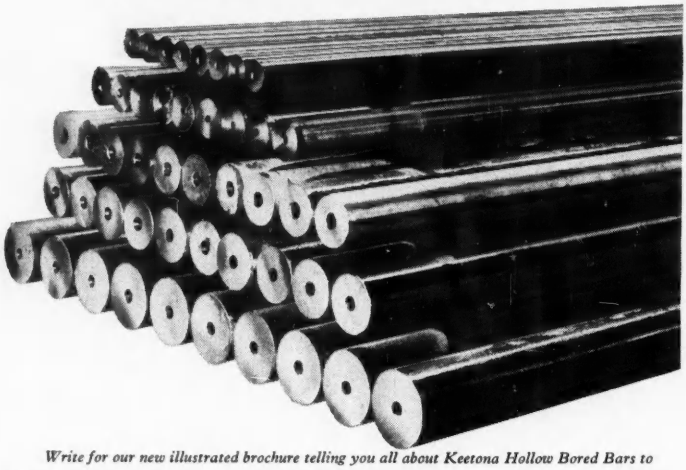

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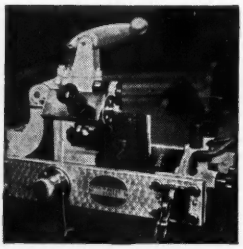

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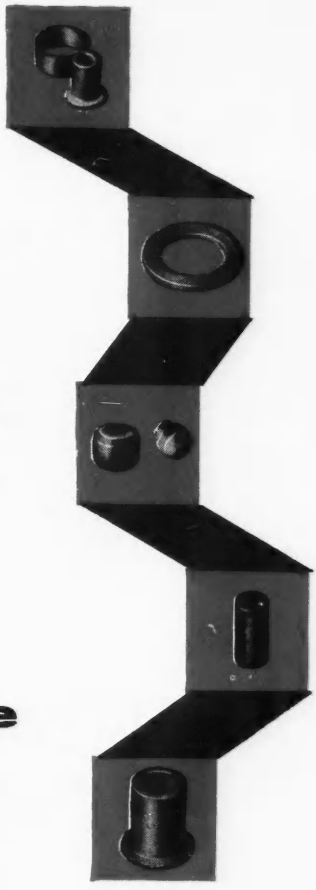

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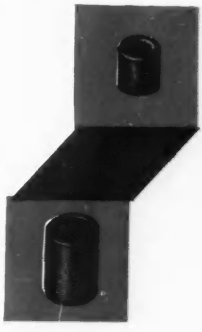

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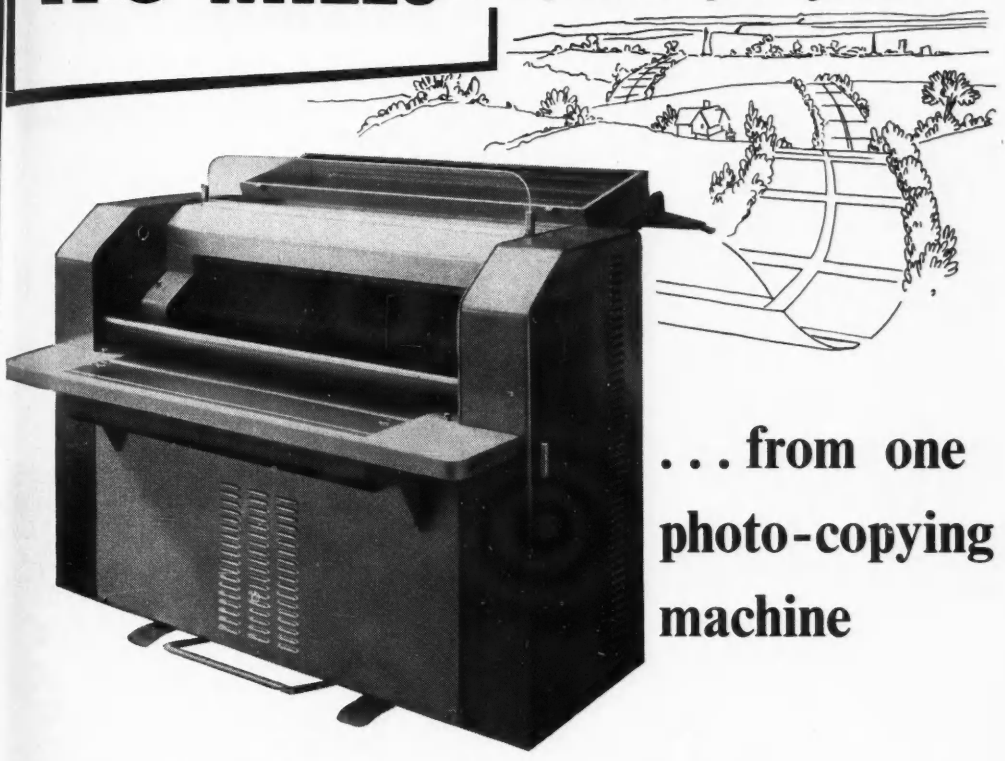

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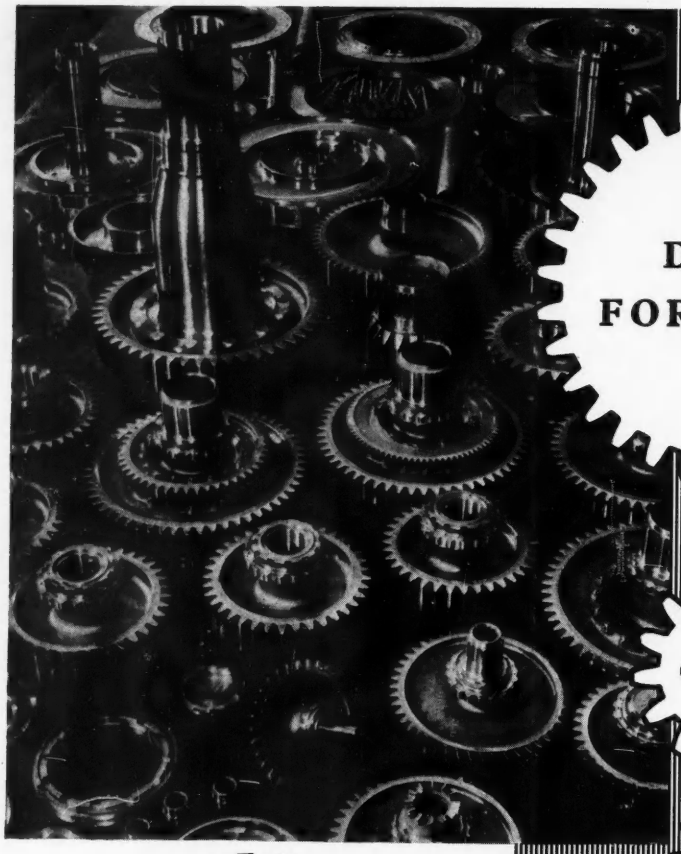

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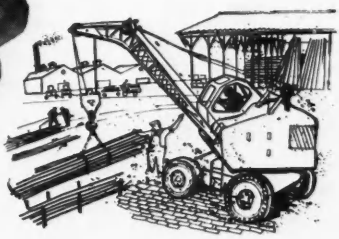

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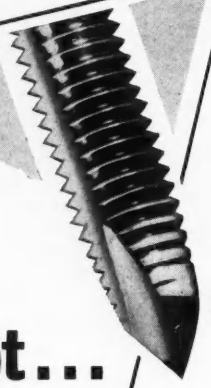

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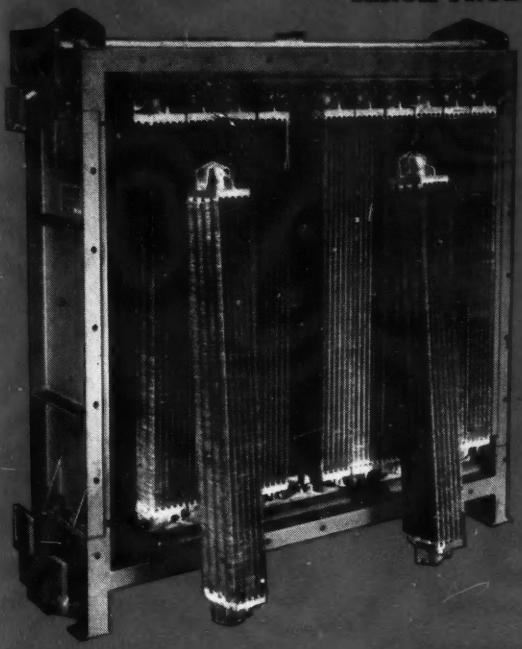

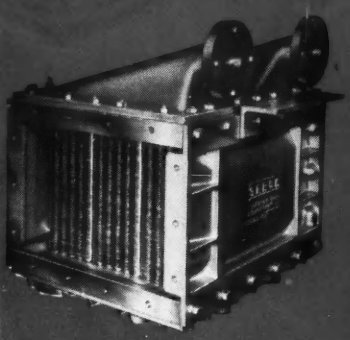

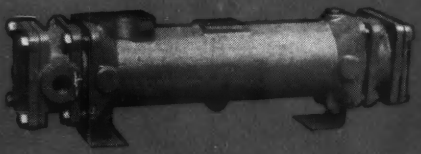

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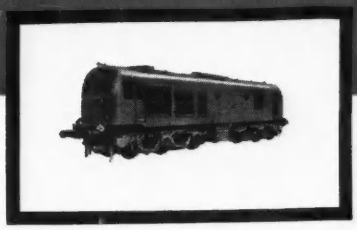

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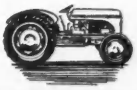

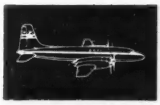

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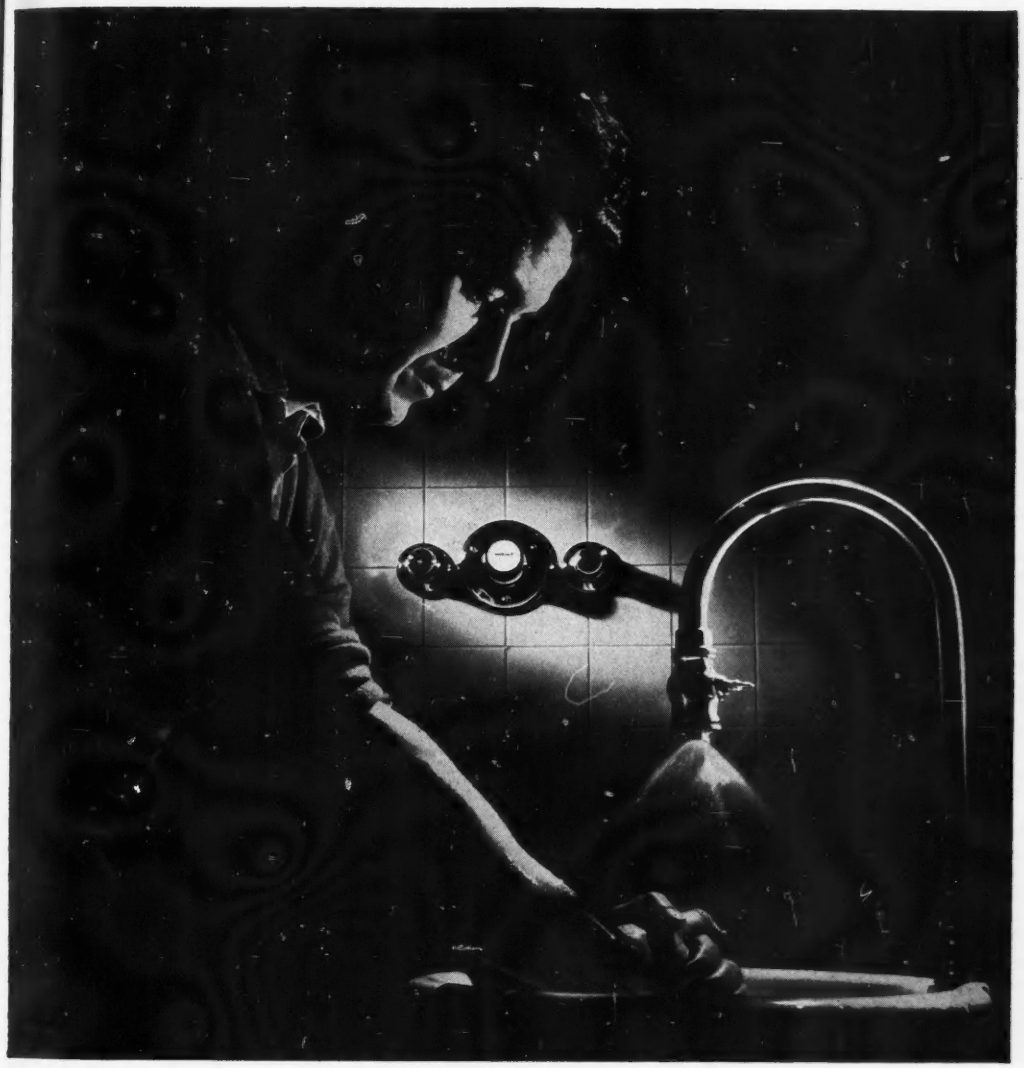

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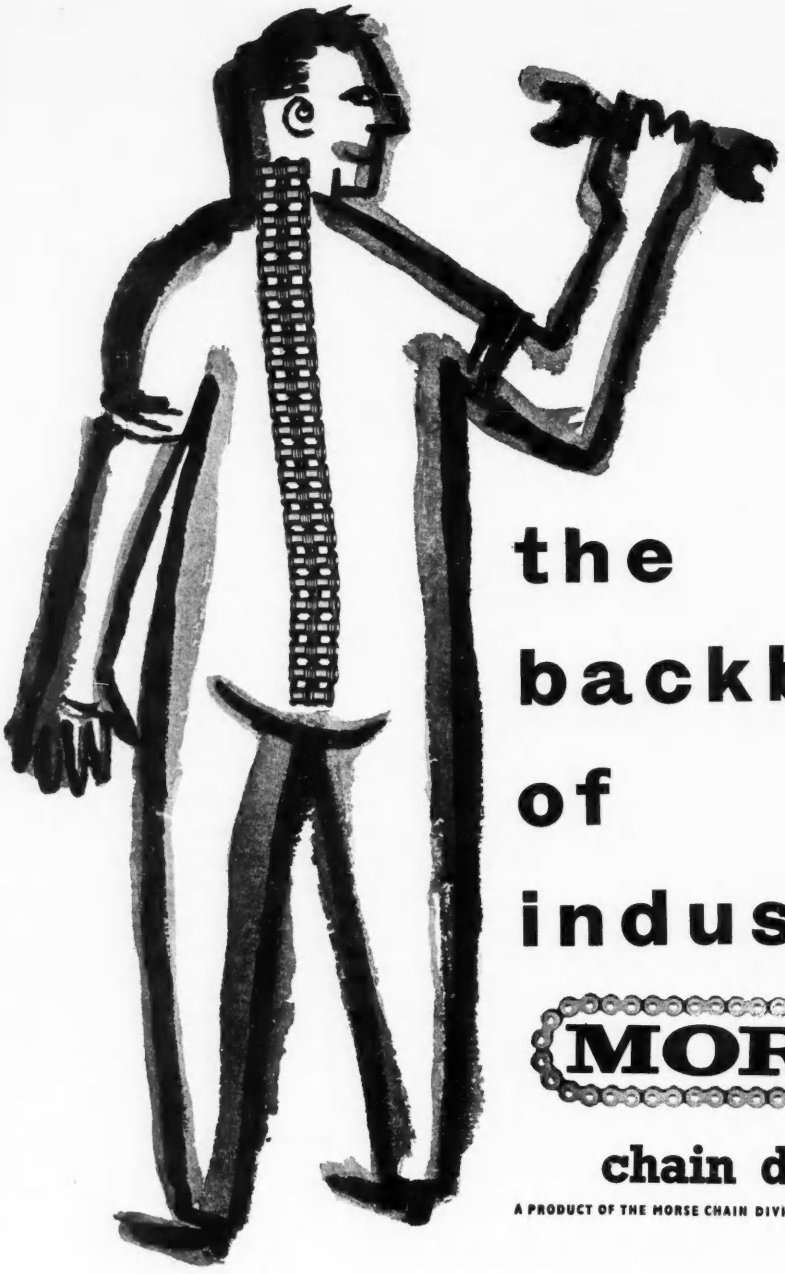

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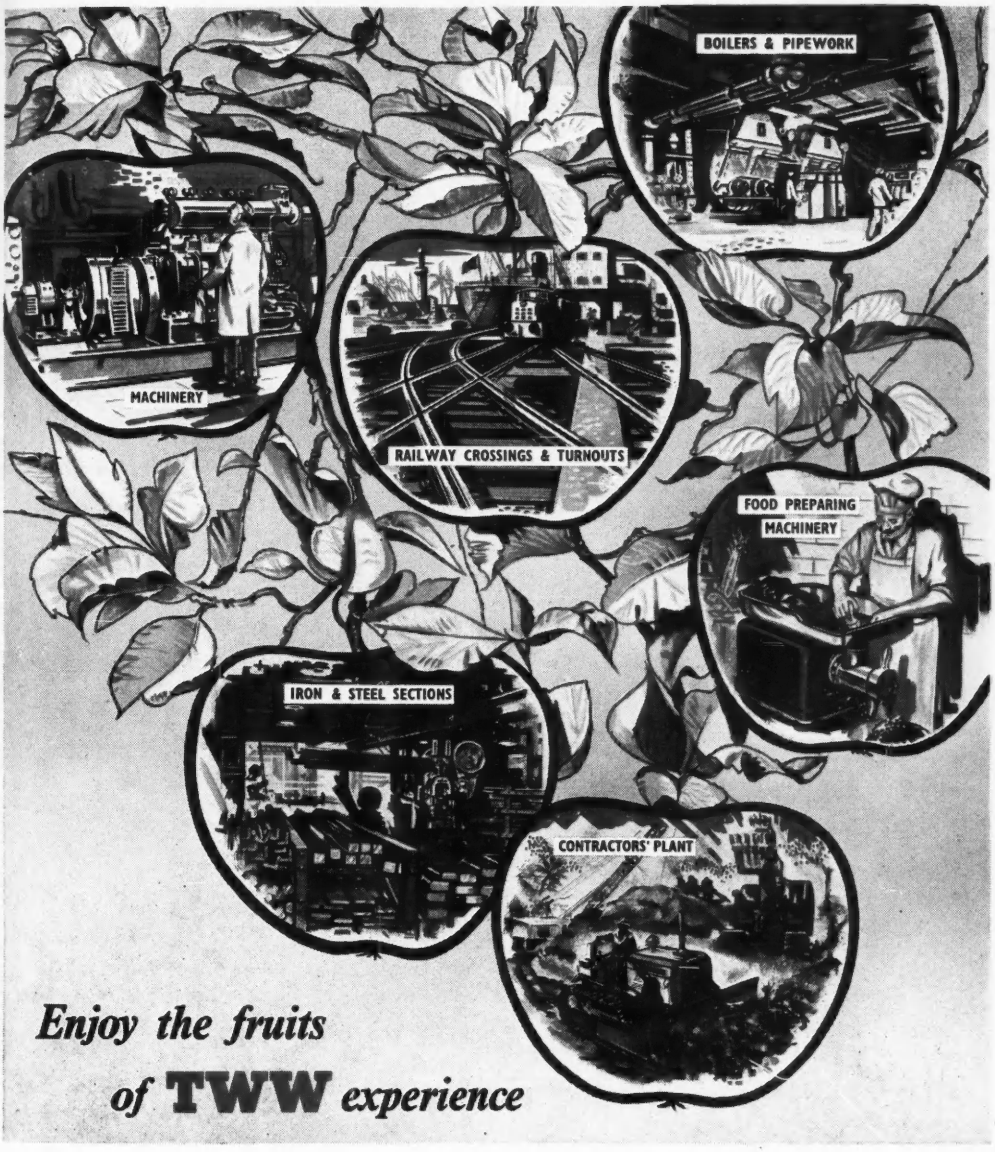

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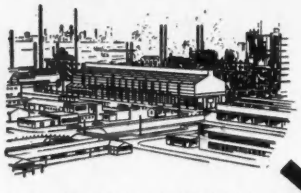

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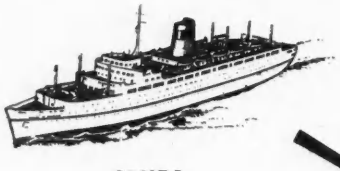

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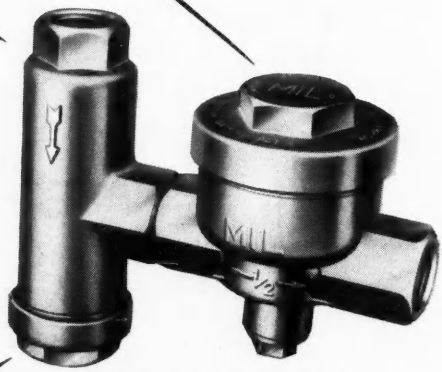

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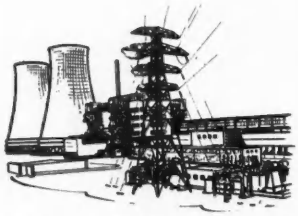

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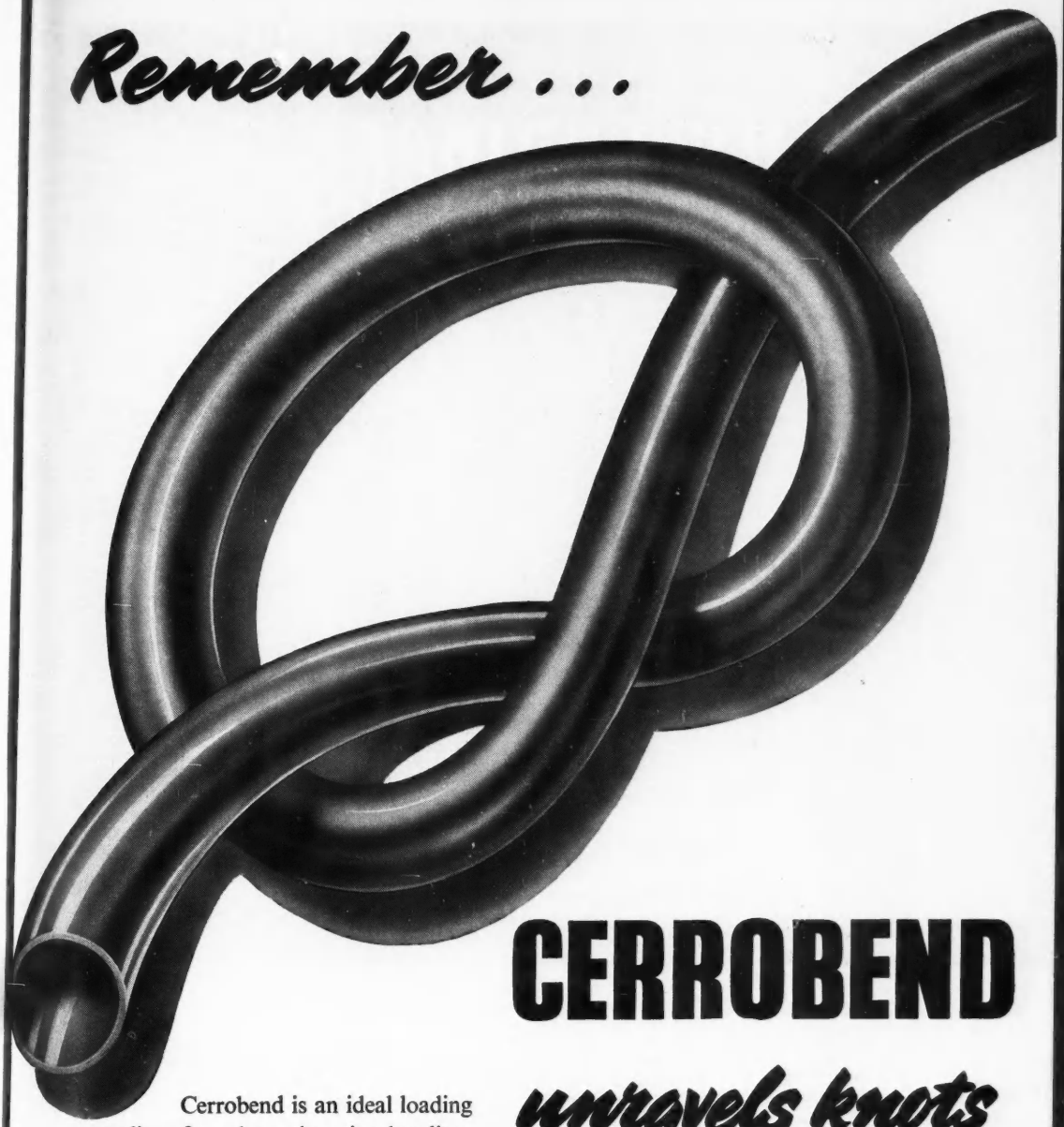

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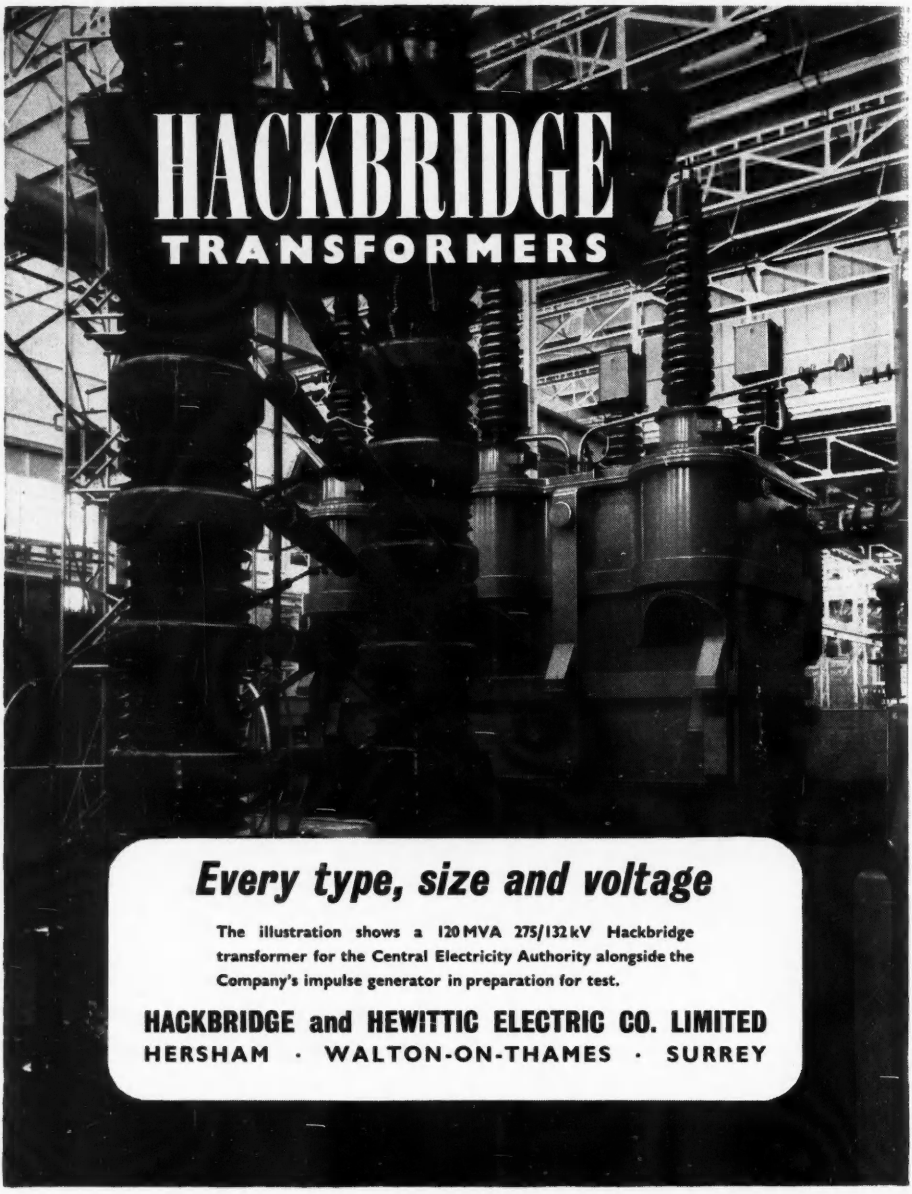
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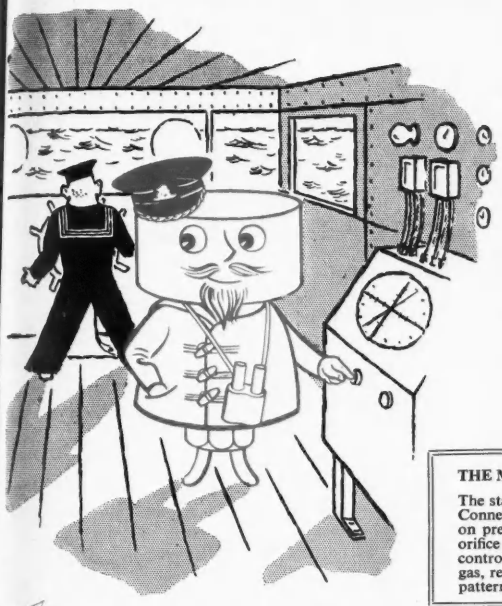

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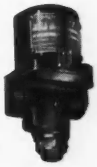

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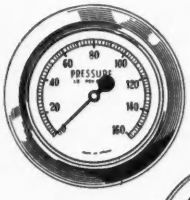

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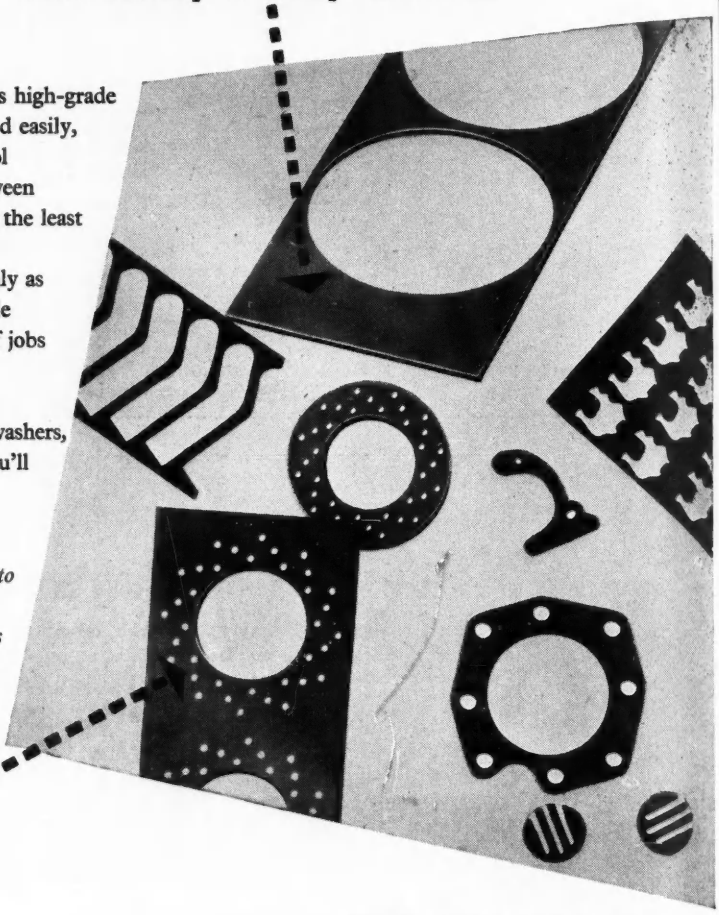
Tufnol punchings can be produced to your specification in our factory. Or Tufnol can be supplied in sheets or strips for punching in your own workshops. Write for further information.



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An ELLISON Product

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"Newallastic" bolts and studs have qualities which are absolutely unique. They have been tested by every known device, and have been proved to be stronger and more resistant to fatigue than bolts or studs made by the usual method.

C. P. Newall & Co., Ltd.

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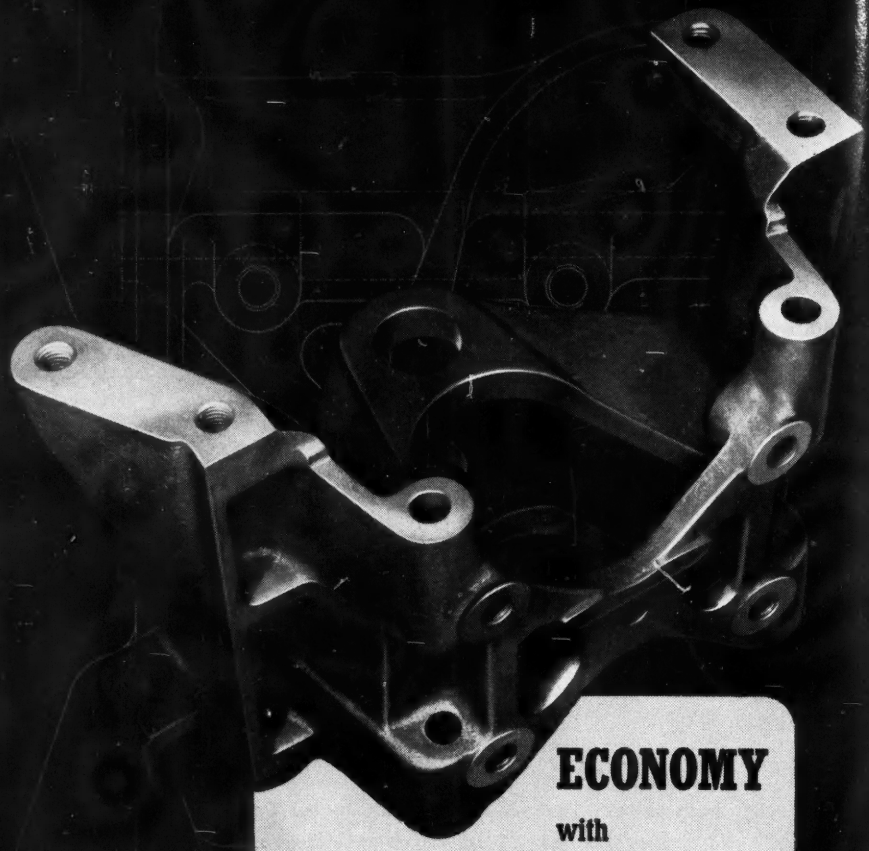


ECONOMY

with

Ley's 'Black Heart' Malleable Castings

This front engine mounting bracket for a tractor is a single casting replacing an assemblage of numerous parts.
The castability of this material permits effective distribution of the metal and is typical of the many applications where economical production results from the use of Ley's 'Black Heart' Malleable.

LEY'S MALLEABLE CASTINGS CO. LTD., DERBY
Telephone: Derby 45671

EUROPE'S LARGEST MALLEABLE PRODUCERS

LEY'S

Variable-speed drives by L.S.E.

L.S.E. can offer in most instances the correct type of electric motor or system for variable-speed drives. In addition to the N-S motor (see advertisement page A70), the following are available :

The " SPEEDMASTER " and variable-speed squirrel-cage motor drives

The " Speedmaster " is a single unit self-driven frequency convertor which provides a variable-frequency supply for squirrel-cage motors used as variable-speed machines where a number must be operated in unison. On group drives, N-S motors may be employed where individual speed trimming, relative to the group speed, is required.

For fixed low frequency supply (and in some instances for variable-frequency) an alternative machine, the N-S Convertor, is available. This is used with low-speed gearless drives, for example, or high-speed drives which have to be run intermittently at low speeds.

The " REVCON " control system

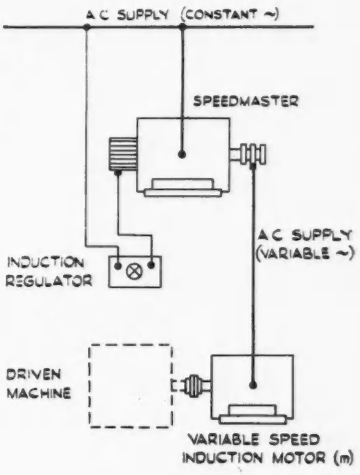
Mainly applicable to crane hoist motions and similar drives, the " Revcon " system gives stable speed control within a wide range, hoisting or lowering, to a degree impossible with a standard slip-ring motor equipment.

The motor is a single induction motor, without commutator or additional rotating equipment. No friction brake is required to control the load. The control system is based on the superimposition of a braking torque on a motoring torque.

Speed control from a crawl to full speed is obtainable at all loads and a light-load high-speed step of twice full-load speed is provided.

D.C. MOTORS

Where direct current is available the use of d.c. motors for variable-speed drives is usually advantageous, and conversion to d.c. may sometimes be justified. A d.c. motor can be designed to give almost any required speed/torque characteristic by field and/or voltage control, speed ranges up to about 100:1 being possible.



Schematic diagram of " Speedmaster " frequency convertor. The induction regulator may be adjusted by hand, from remote push-button, or from an automatic device actuated by pressure, thickness, tension, speed of another machine or process line, or other measurable quantity or condition.

Fuller details of the above machines will be furnished on request to any L.S.E. Branch or to Publicity Dept., 376 Strand, London, W.C.2.

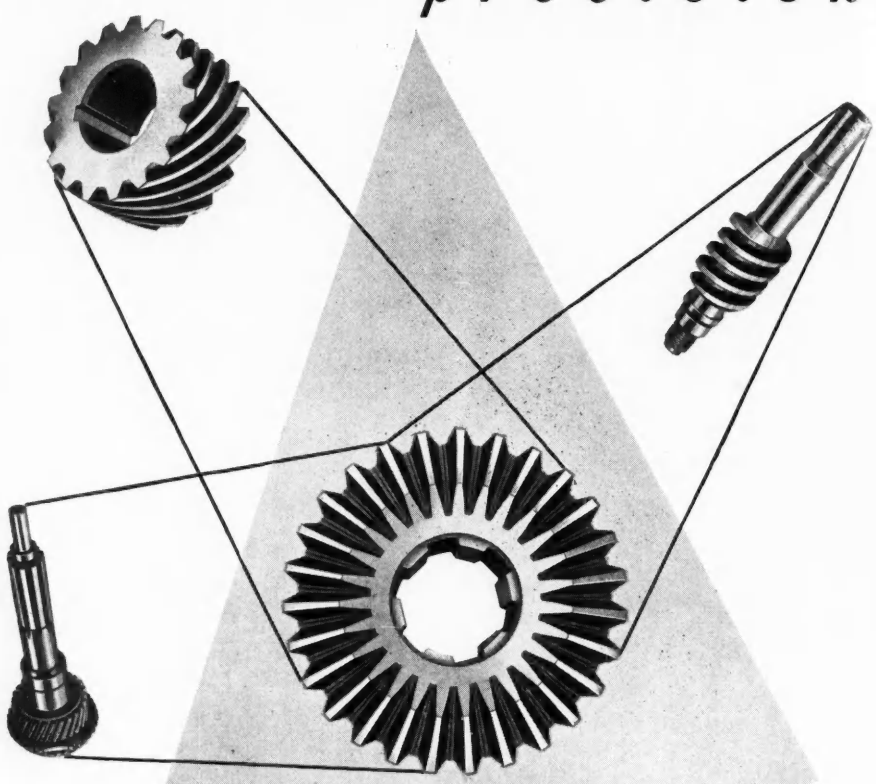
Some indication of the type of possible application should be given in any general enquiry.

LAURENCE, SCOTT & ELECTROMOTORS LTD

Specialist Makers of Electric Motors Since 1883

NORWICH, MANCHESTER, LONDON & BRANCHES

precision



is the background

We have a standard range of Automotive and Industrial Gear Boxes, or can undertake the supply of loose gears and shafts to your own design.

THE GEAR SPECIALISTS

Cut, ground or shaved Spur and Helical Gears. Ground Worms and Splines — Sprockets — Bevels — Reduction Units — Gear Boxes for all Trades.

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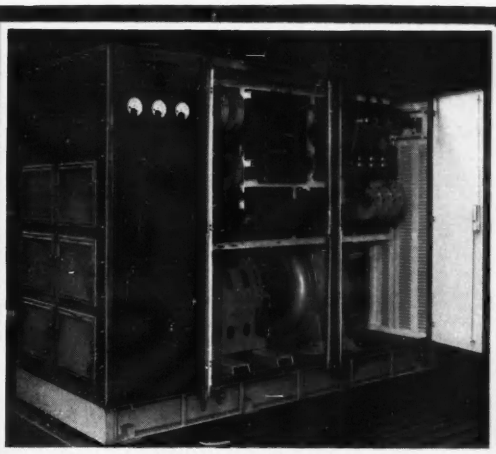
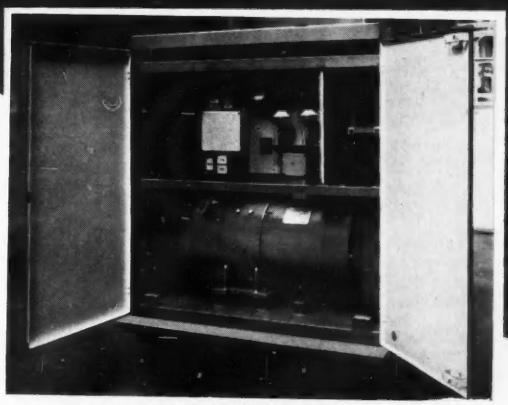
VARIABLE SPEED *PACKAGE* DRIVES



The packaged 100 H.P. Ward Leonard set to supply the main calender motor.
Dimensions 118" W. × 86" H. × 51" D.



The packaged 10 B.H.P Ward Leonard set and electronic gear for synchronising the 5B.H.P. cooling drums and 5 B.H.P. wind-up drives with the main calender.
Dimensions 50" W. × 50" H. × 28" D.

SEVEN STAR FEATURES

- ✲ Saves floor space
- ✲ Reduces site wiring to a minimum
- ✲ Eliminates special foundations
- ✲ Cubicle pressurised with filtered air
- ✲ Easily maintained
- ✲ Electronic Control incorporated where required.
- ✲ Tailored to suit your individual needs

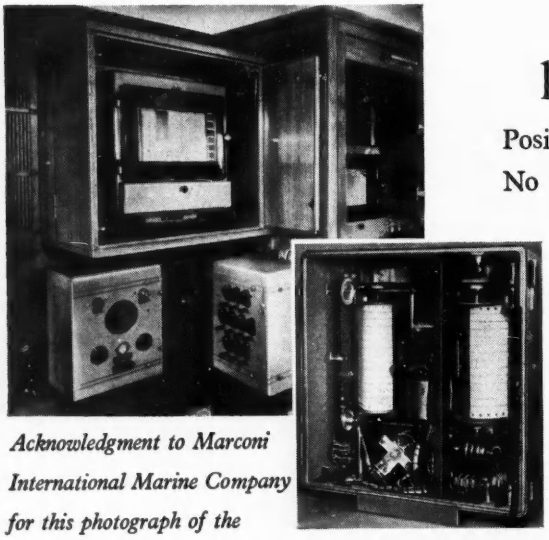
Our specialist engineers will be glad to advise on the best method of control for YOUR drives.

THE ELECTRIC CONSTRUCTION COMPANY LIMITED
WOLVERHAMPTON

3203

US RUBBER POWERGRIP TIMING BELT

for precision echoes



Acknowledgment to Marconi International Marine Company for this photograph of the ***POWERGRIP*** *timing belt on scribing stylus drive.*

Positive elimination of slip and creep • No initial tension • Compactness in width and pulley diameter • No belt stretch—needs no take-up—will operate on fixed centres • High operating speeds • Constant angular velocity • No lubrication required • High mechanical efficiency—very nearly 100% • Light or heavy drives—1/100—300 HP.

In order that the depth and density of shoals of fish in the sea be precisely determined, it is imperative that the movement of the echometer scribing stylus over the sensitised paper be perfectly synchronised with the echo-sounding oscillator.

The POWERGRIP timing belt fitted to Marconi Recording Echometer fulfils the required accuracy of drive, ensuring accurate performance of these precision instruments.

US RUBBER **U. S. Rubber**

Home: *The North British Rubber Company Limited. ABBey 7135*
Export: *U.S. Rubber International (Great Britain) Ltd. ABBey 2053*

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A.C. VARIABLE SPEED COMMUTATOR MOTORS

The first ever shunt characteristic A.C. Variable Speed Commutator Motor was developed and patented by ASEA in 1910, and the commutator motors manufactured by us, under licence, to the ASEA modern designs incorporate the same basic principles and all the experience gained during the years. These motors have been tested and proved sound by their installation in a wide variety of applications all over the world.

Infinitely Variable Speed—Stepless, smooth and infinitely variable speed control is obtained throughout the range—the EXACT speed to suit every condition of service.
Speed Adjustment—Speed control is by simple brush displacement; there are no resistances or external regulators. Adjustment of the motor speed is obtained by handwheel or alternatively by remote powered control, to exactly the value required. An alternative system of power operation for the brush gear permits remote control in many convenient forms.
Speed Range—There is no technical limit to the range obtainable; for example 0 to 3,300 r.p.m. has been provided for certain special drives. The standard range (approximately 4 to 1) gives the most economical form of motor and is generally sufficient for most requirements.
Shunt Characteristic—Stable speeds practically independent of loading are obtained throughout the standard speed range. Speed fluctuations under load are no more than experienced with D.C. shunt wound motors.
Torque Characteristics—The motor develops constant torque throughout the speed range. Starting torque is over 200 per cent for standard motors.
Electrical Characteristics—Very high power factor at top speed (Unity in many cases) assists in keeping factory kVA maximum demand at the lowest possible level.

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S.T.C.
RECTIFIERS
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for speed control
of D.C. motors

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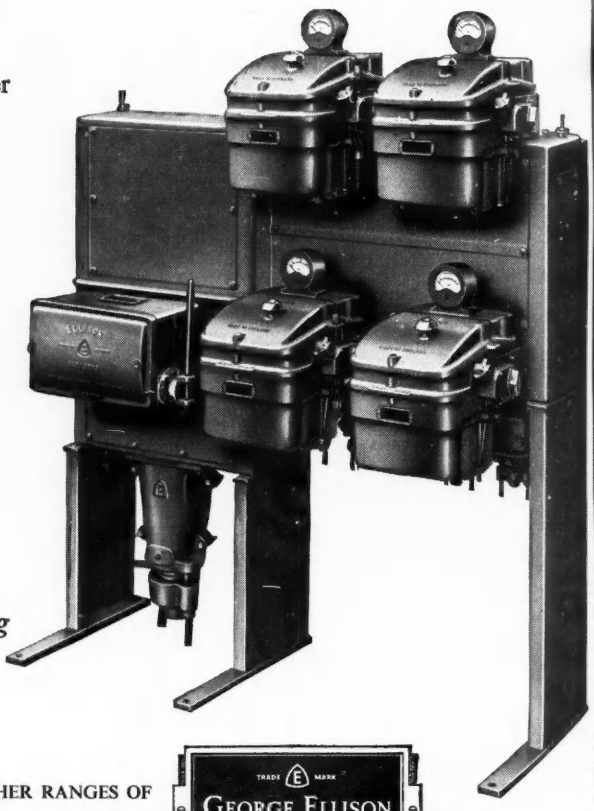
Ellison 20 amp. Circuit Breaker

For Group Mounting and Sequence Starting of electric motors

The "Ellison" 20 amp. direct-to-line starter can readily be mounted in groups on a busbar chamber. Cable entry may be direct to the busbars by way of a cable fitting or through an isolator or automatic circuit breaker. Extensions are easily made.

This A.S.T.A. tested gear has a built-in isolator in which H.R.C. fuses may be included. Auxiliary switches may also be incorporated for sequence starting. Robust contacts ensure long life under direct-to-line starting conditions.



With reliable quick-resetting protective devices and safety interlocks

WRITE FOR INFORMATION ON OTHER RANGES OF ELLISON STARTERS FOR MOTORS OF UP TO 1000 B.H.P.

TRADE (E) MARK
GEORGE ELLISON
LIMITED
BIRMINGHAM ENGLAND

YOU CAN RELY ON AN ELLISON PRODUCT

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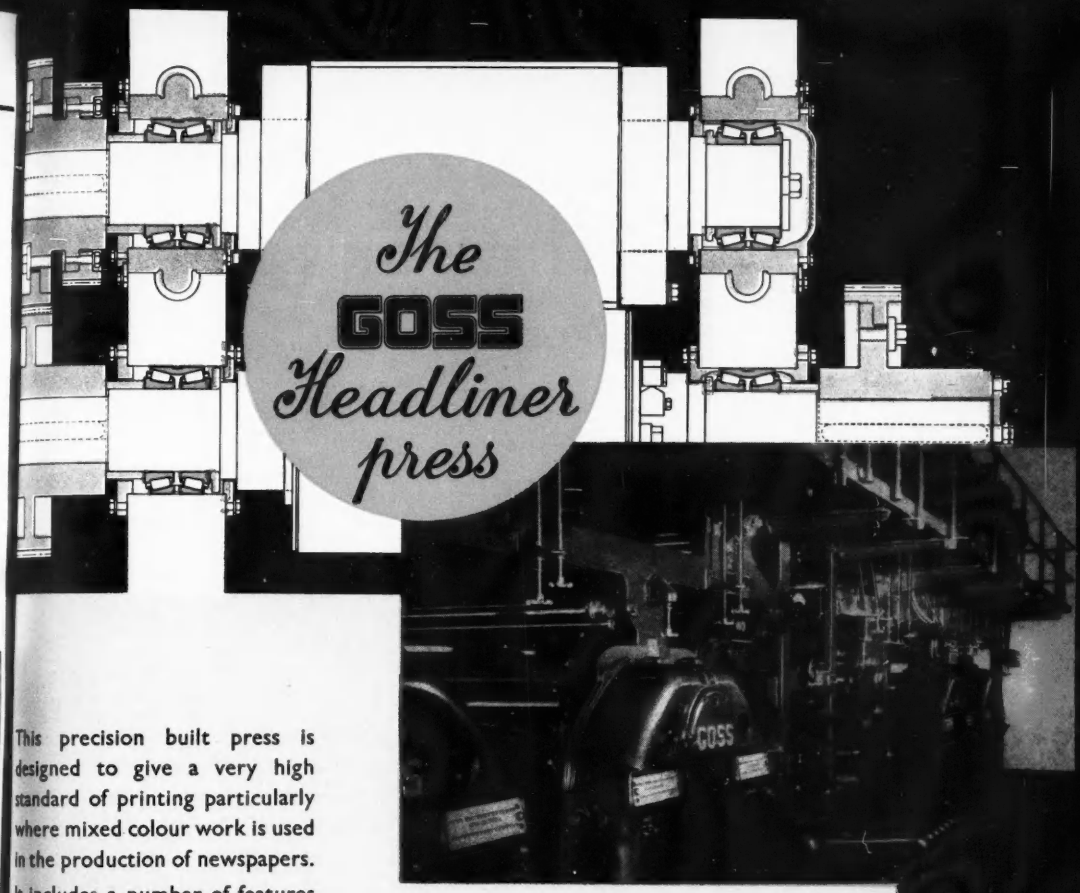

This precision built press is designed to give a very high standard of printing particularly where mixed colour work is used in the production of newspapers. It includes a number of features which enable the most precise adjustments to be made, and to facilitate colour changes without wastage of ink and labour. The cylinders as shown in the drawing are mounted upon pre-loaded Timken double-cup tapered-roller bearings. Both cylinders are end-located by the bearings at the right, the bearings at the left (although pre-loaded within themselves) are free to float. In this arrangement temperature variation cannot interfere with the bearing tightness; errors in printing register due to play between the cylinders are thus avoided.

The inset housings for the upper bearings have their exteriors eccentric to the bores; a micrometer adjustment for the printing impression is thus obtainable by slightly rotating the housings.

TIMKEN

Regd. Trade Mark TIMKEN

tapered-roller bearings

MADE IN ENGLAND BY BRITISH TIMKEN LTD.

DUSTON, NORTHAMPTON (HEAD OFFICE): DAVENTRY AND BIRMINGHAM
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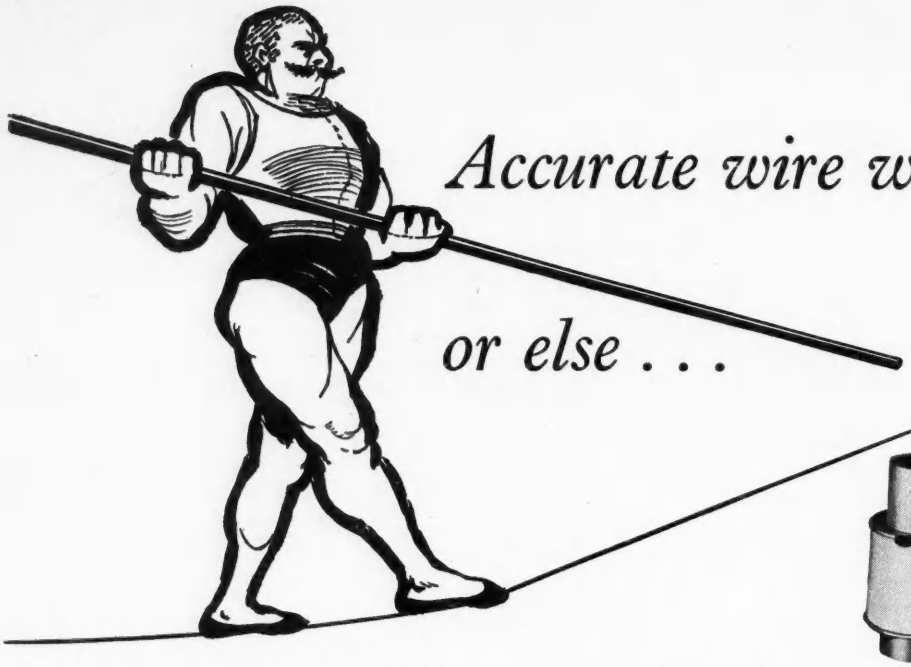
SUBSIDIARY COMPANIES: FISCHER BEARINGS COMPANY LTD., WOLVERHAMPTON, TIMKEN-FISCHER STOCKISTS LTD., BIRMINGHAM

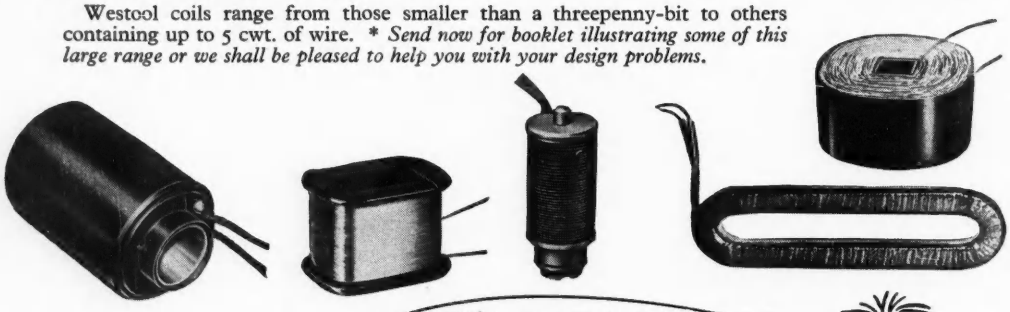


Accurate wire work or else . . .

We *wind* wire but in our business too we cannot afford to be anything but highly accurate. The fact that over a million coils are produced every year in the Westool works is a clear indication that we meet the high standards of accuracy and reliability that our customers demand.

Westool coils are wound on Westool coil winding machines, designed from experience gained over many years. We have machines that will wind coils at very high speeds yet still maintain extreme accuracy; machines capable of winding wire finer than a human hair; machines that will mass produce coils with all the qualities of a "one-off" job.

Westool coils range from those smaller than a threepenny-bit to others containing up to 5 cwt. of wire. * *Send now for booklet illustrating some of this large range or we shall be pleased to help you with your design problems.*



DON'T BE PREHISTORIC— take advantage of Westool's modern coil winding techniques

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Westool also make: Transformers and Chokes, Small Motors, A.C. and D.C. Solenoids, Vibrating Tables, Grinding Attachments, Air Conditioners, Warner Electric Brakes and Clutches.

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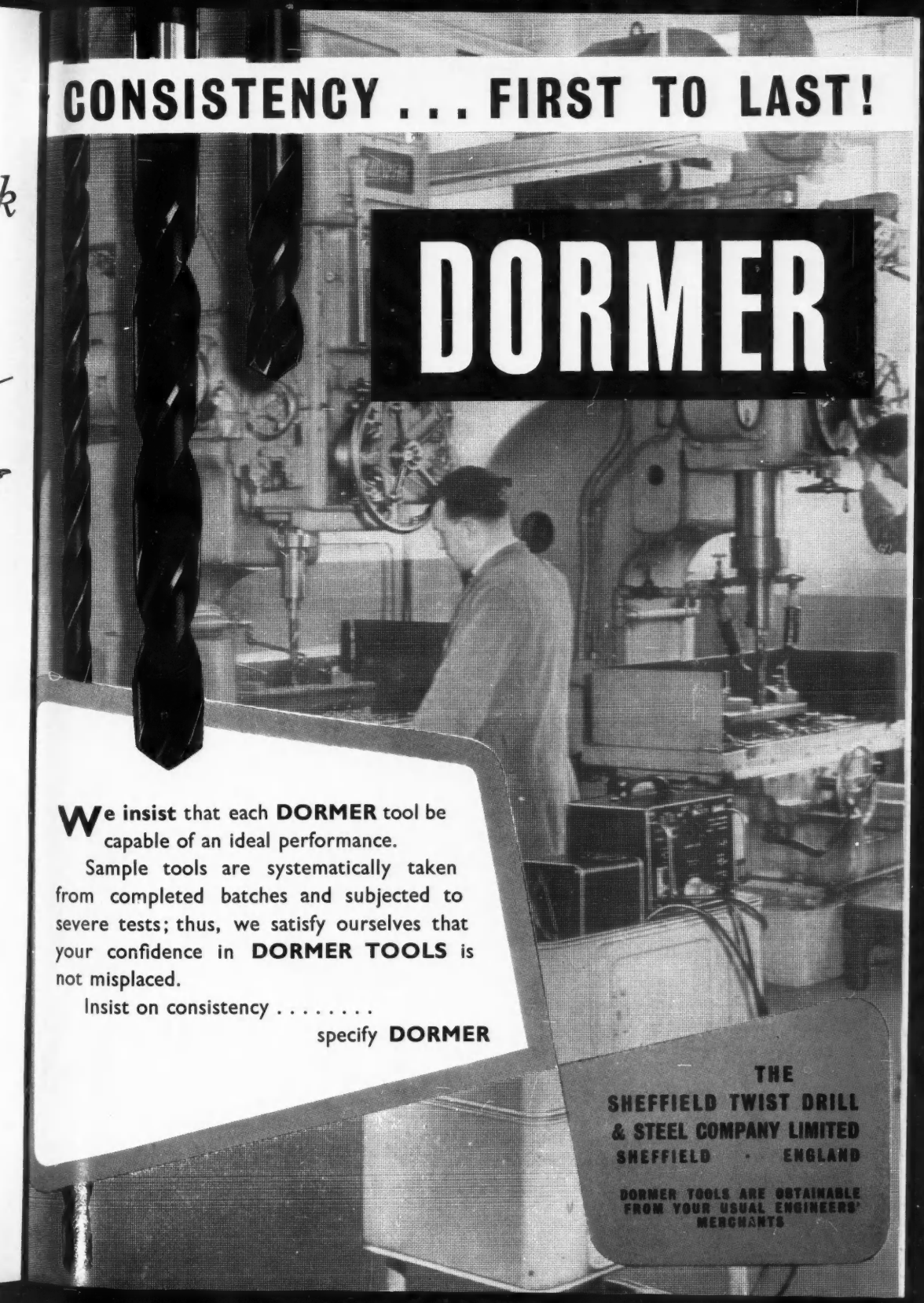
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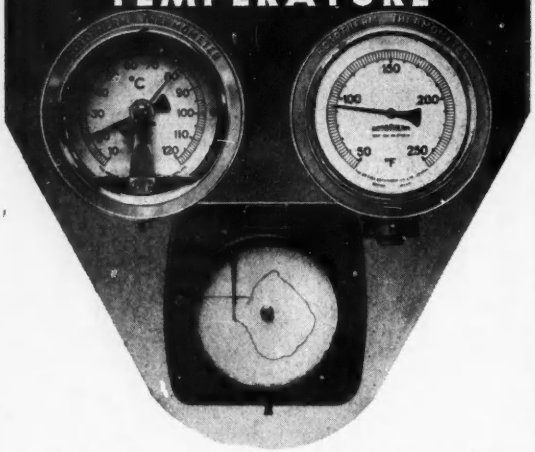

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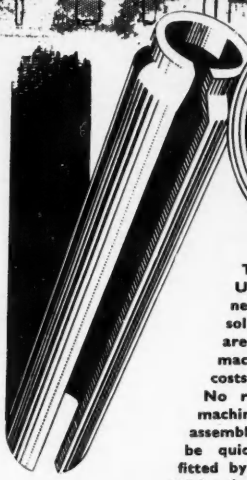

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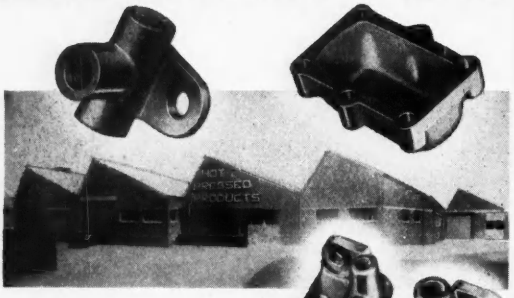

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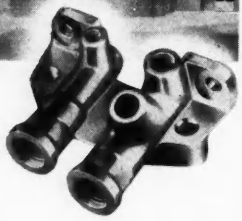

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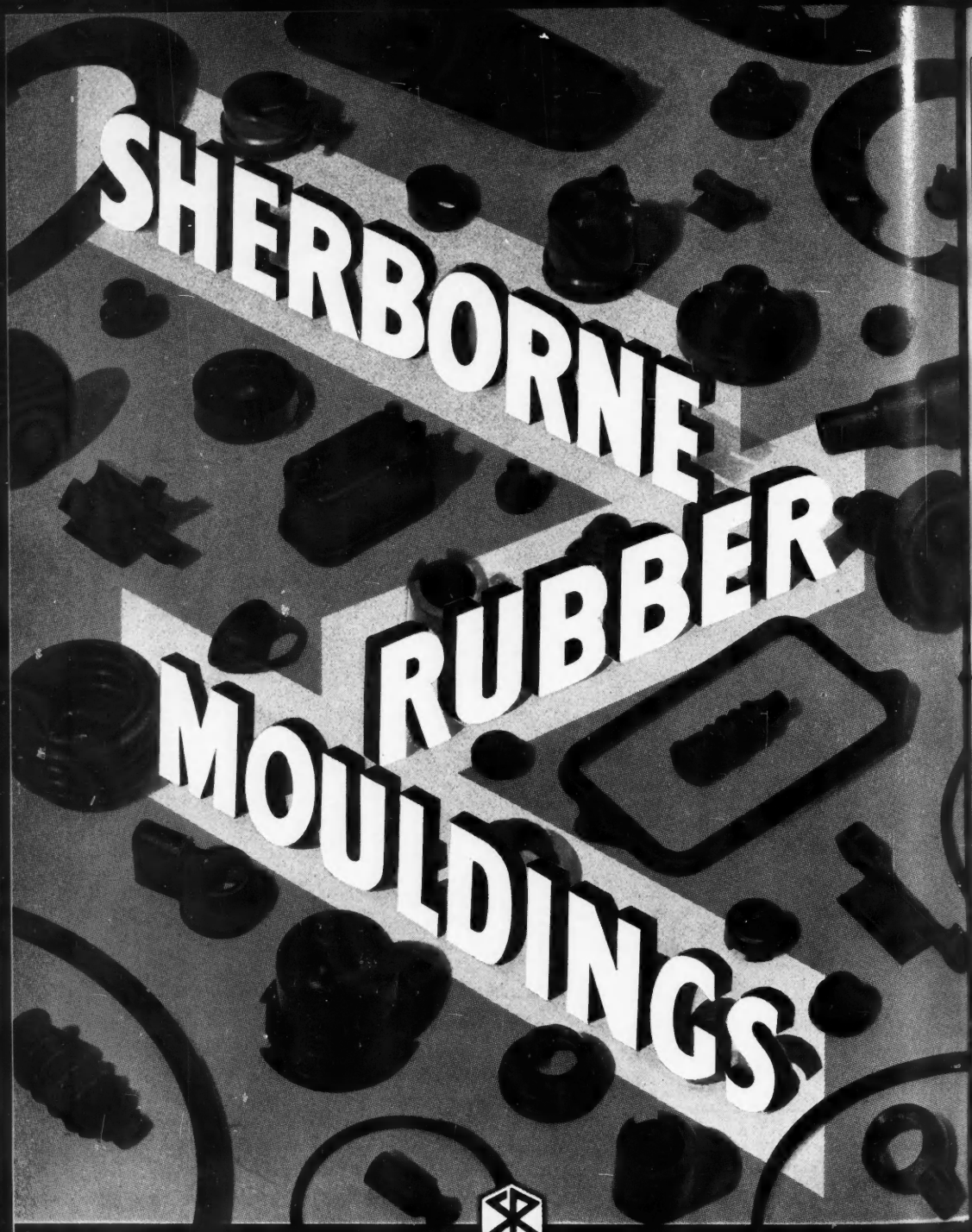

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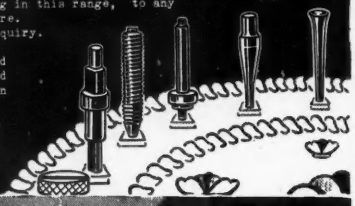

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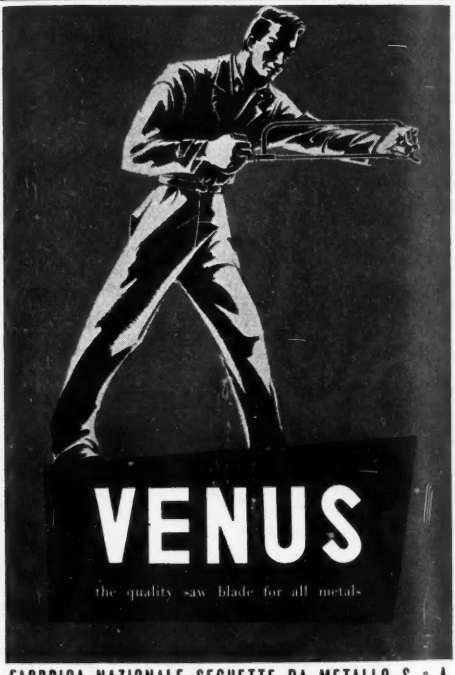

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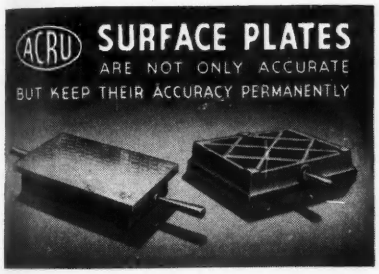

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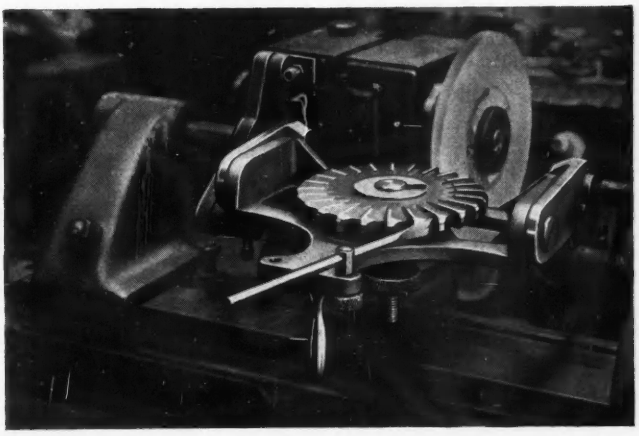

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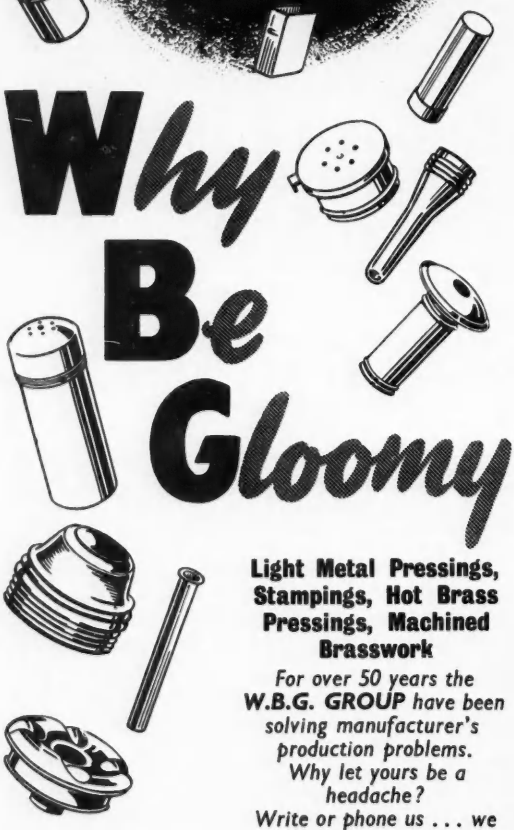

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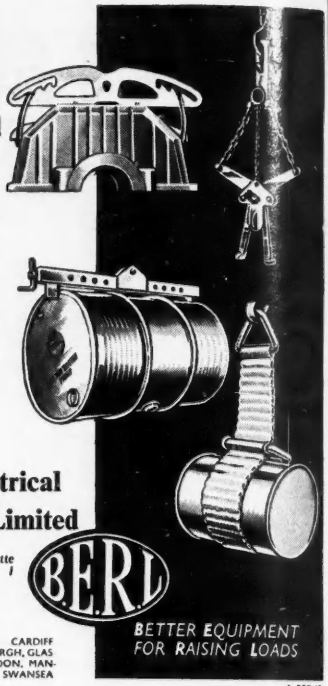

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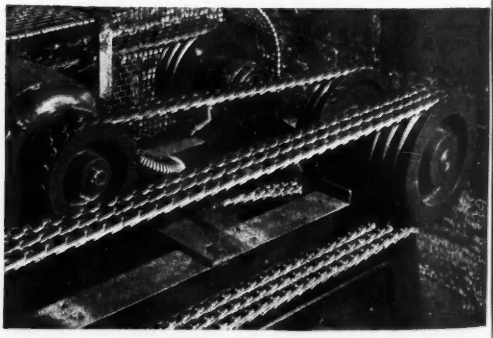

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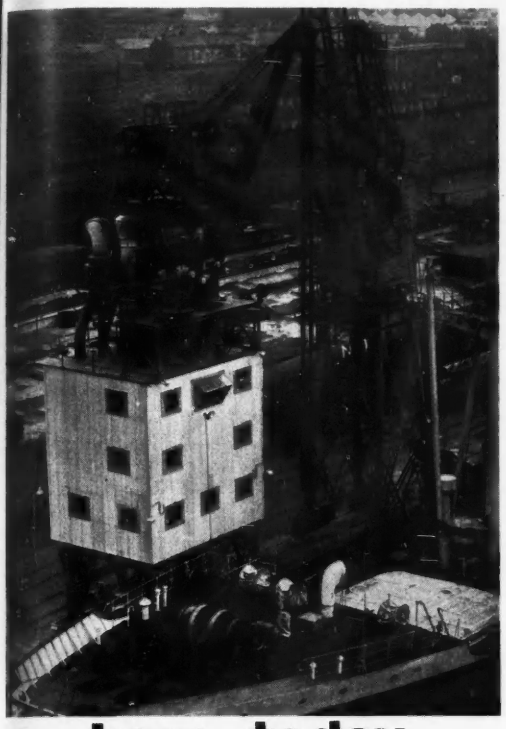

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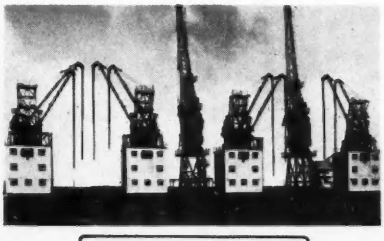

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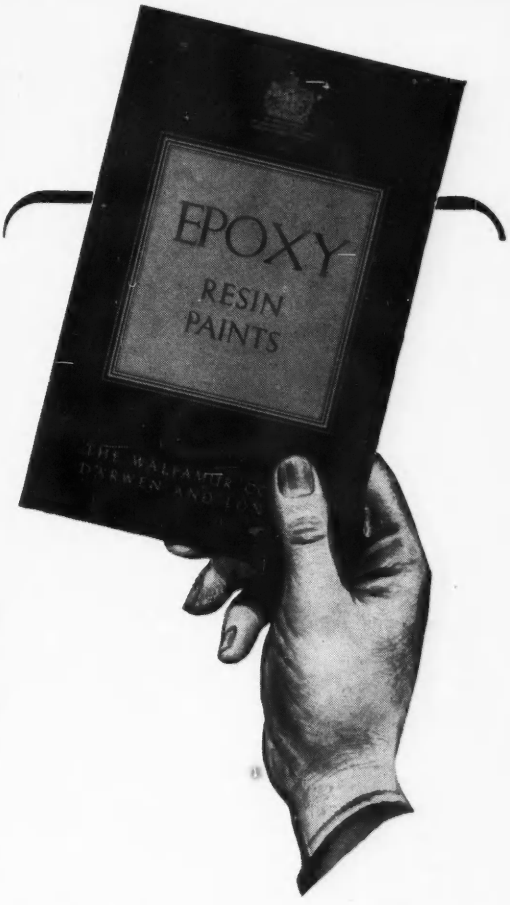

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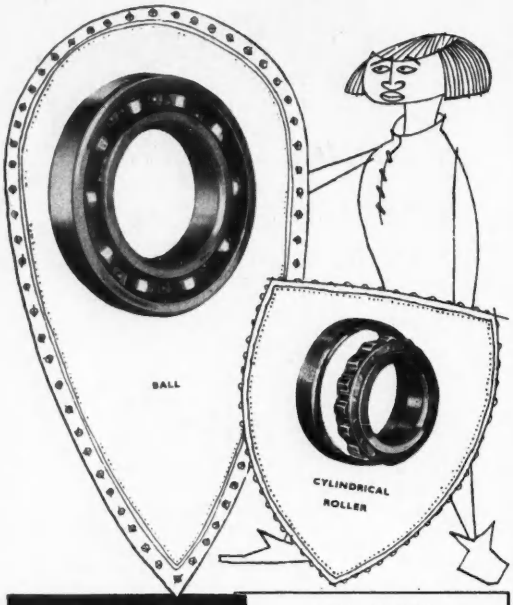

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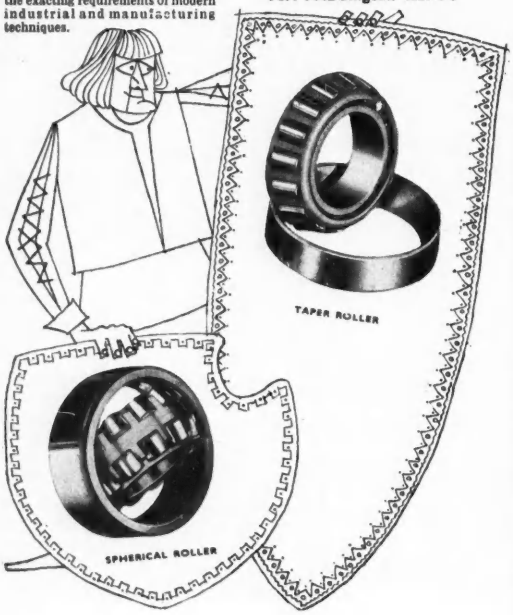

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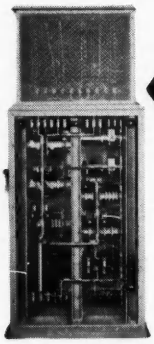

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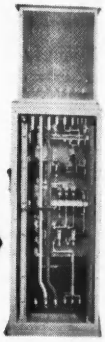

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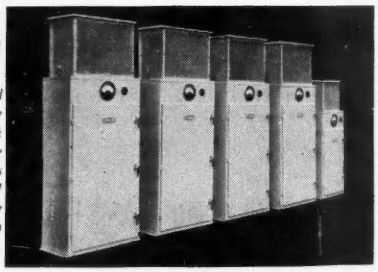

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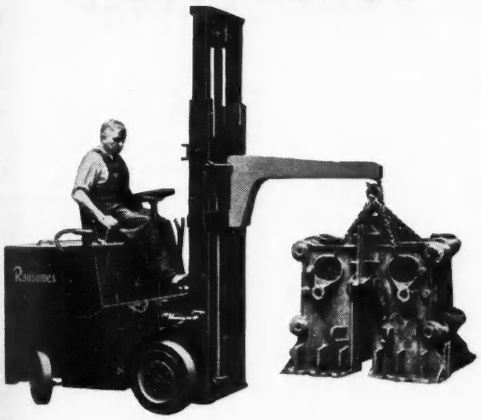

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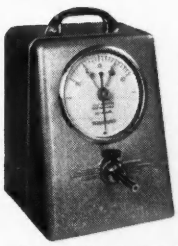

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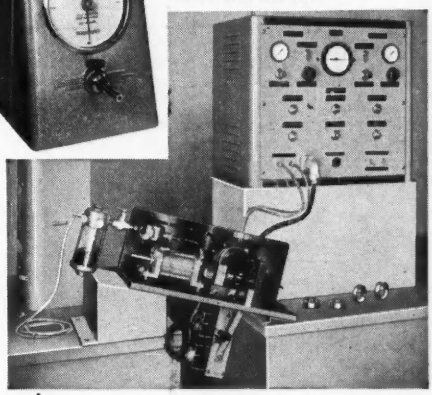

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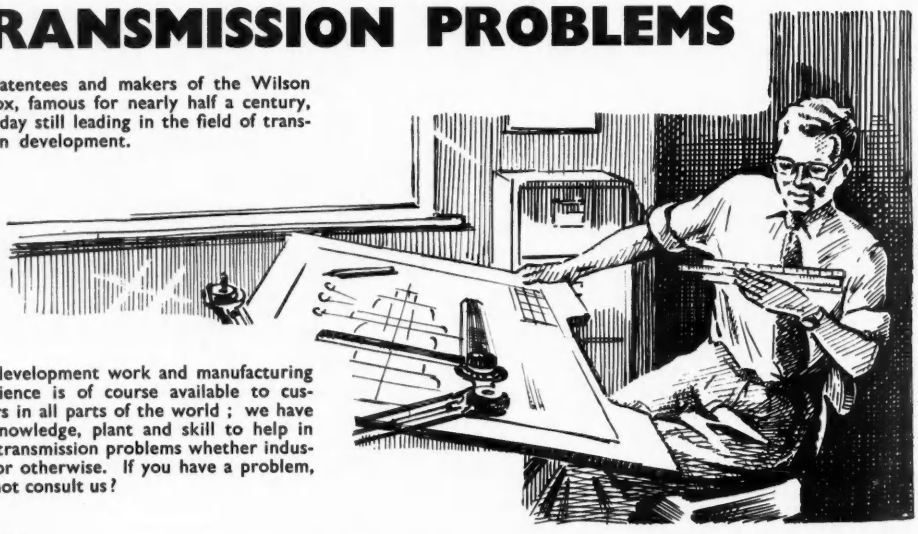

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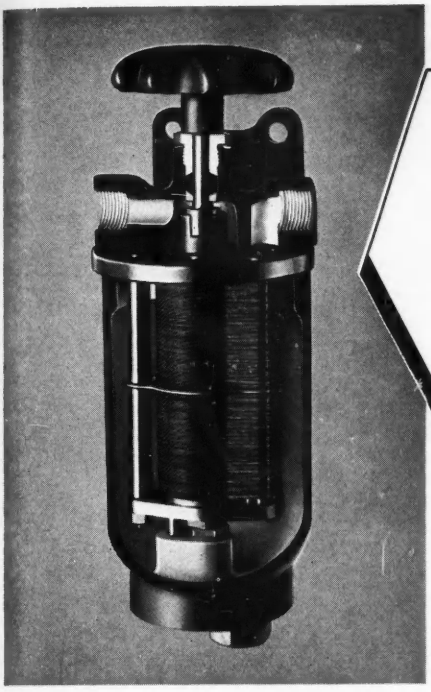

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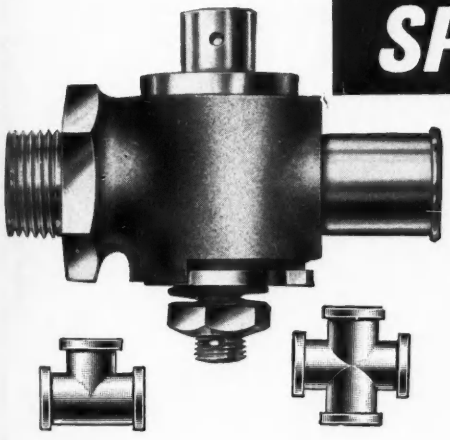

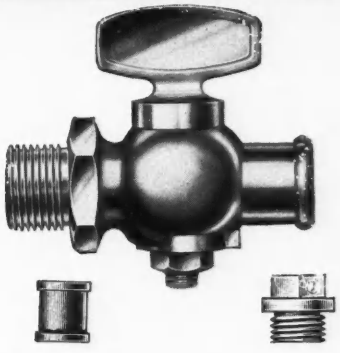

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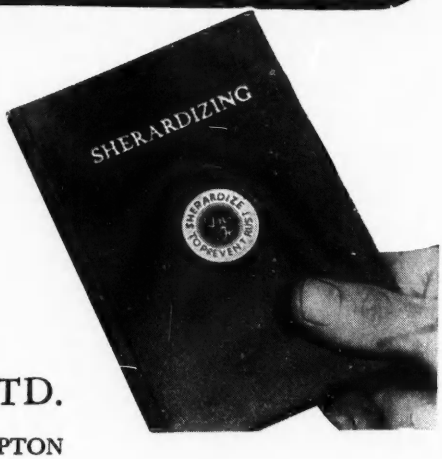

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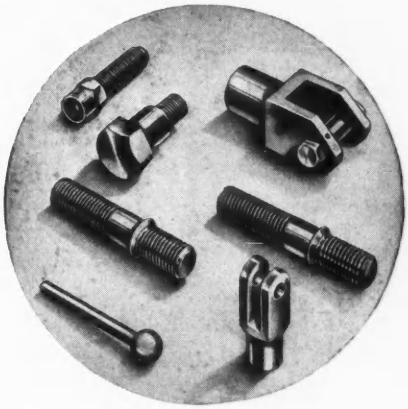

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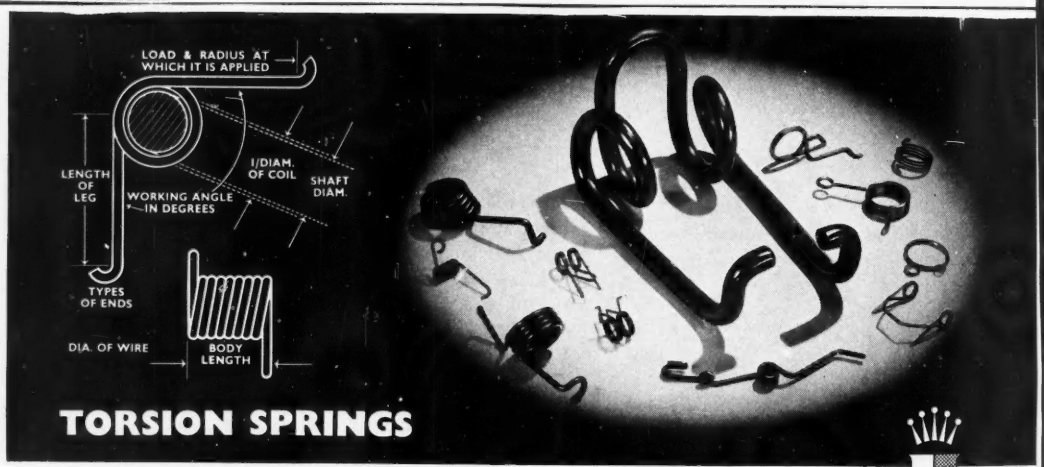

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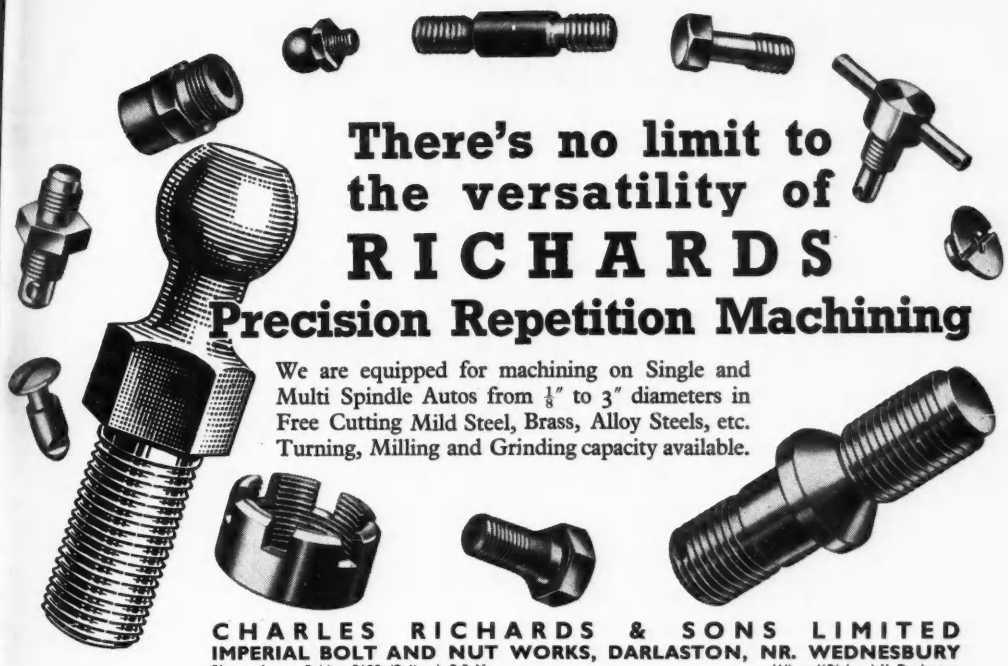

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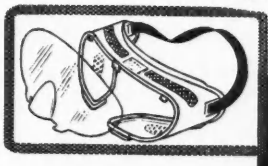

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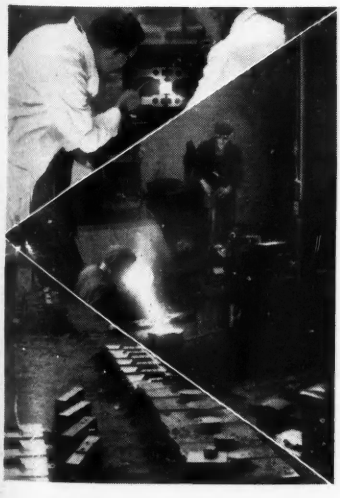

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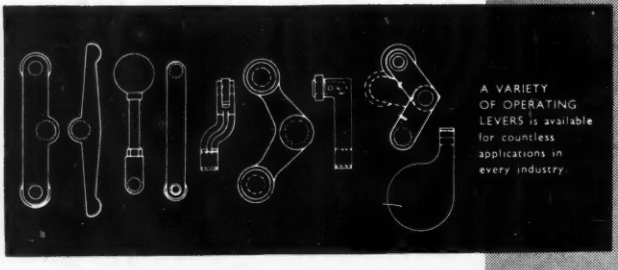

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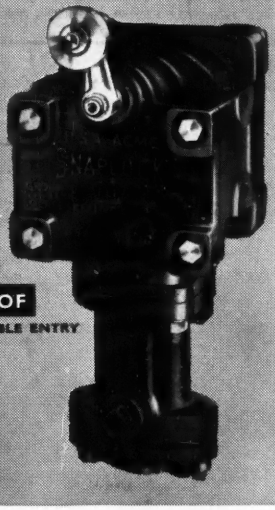

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